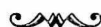


The Institution of Mechanical Engineers



James Clayton Lecture

CAVITATION MECHANICS AND ITS RELATION TO THE DESIGN OF HYDRAULIC EQUIPMENT

By Professor Robert T. Knapp, Ph.D.

*The lecture to be delivered in London on
Friday, 18th April 1952, at 5.30 p.m.*

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JAMES CLAYTON LECTURE

Cavitation Mechanics and its Relation to the Design of Hydraulic Equipment

By Professor Robert T. Knapp, Ph.D.*

The objective of this lecture is to outline the various characteristics of the cavitation phenomenon and to point out in general how this knowledge may be used to alleviate and, in some cases, to eliminate the losses due to damage of materials and decrease in performance of hydraulic equipment. It is shown that difficulty with cavitation is encountered over the entire field of hydrodynamics but that, although the manifestations may appear to differ widely, they can usually be understood on the basis of present concepts of the mechanics of cavitation. It is found that such understanding usually brings with it suggestions of methods for lessening or eliminating the difficulty.

INTRODUCTION

Cavitation is one hydraulic phenomenon in which the effects are predominantly undesirable and often destructive. It is true that in a few applications its characteristics are deliberately employed for a constructive purpose; for example, as the means of limiting the capacity of special centrifugal pumps. However, in the majority of cases the inception and growth of cavitation set an upper limit on the performance of hydraulic equipment and prevent the engineer from doing many useful things. The bad effects of cavitation are numerous. One of the most commonly recognized and economically significant effects is the damage that it does to hydraulic structures and machines. Indeed, cavitation damage is so common and so serious that by many people it is thought of as the phenomenon itself rather than as an effect of which the cavitation is the cause.

EFFECTS OF CAVITATION

Cavitation Damage. Engineering journals contain many descriptions of the destructive effects of cavitation damage. The civil engineer encounters it in hydraulic structures. A single flood, which passes over the spillway or through the outlet works of a dam, may leave in its wake cavitation damage that will cost thousands of pounds to repair. Under such conditions many cubic yards of concrete may be removed in an incredibly short time. Needle valves, spillway gates, and seats have been badly damaged as the result of cavitation. In the machinery field, damage to hydraulic turbines is common. Here the affected area is usually found near the discharge end of the runner passages and in the draft tube, as well as in the relief valve and associated energy dissipation devices. Similar cavitation damage may occur in the impellers of centrifugal pumps, particularly in large units. Fig. 1, Plate 1, shows two examples of very severe cavitation damage: (a) a small pump impeller and (b) a Francis turbine runner.

With large pump or turbine installations the plant designer is constantly urged to keep the initial cost as low as possible. This tends to maintain to a minimum the margin of safety against cavitation. Unfortunately, the present knowledge of the factors controlling cavitation is still incomplete. The result is that all too frequently the designed margin of safety is found to be insufficient when the plant is put in operation. On the other hand, in some installations it may even be economically sound to design deliberately for operation with a limited amount of cavitation, on the basis that the necessary annual repairs may be less expensive than the cost of ensuring cavitation-free operation. Marine propellers are another type of hydraulic

machine in which cavitation damage is commonly encountered. This is particularly true of high-speed ships. Some of the fast liners have the reputation of requiring major repairs to the propellers or even their replacement between each round trip.

This is by no means an exhaustive list of hydraulic equipment in which cavitation damage may occur. Such a list would be practically endless and would include all sorts of auxiliary equipment such as meters, valves, and fittings. It is much more difficult to name a type of hydraulic equipment in which cavitation damage is never encountered than it is to add new items to the list of damaged equipment.

Effects of Cavitation on Performance Characteristics. Although cavitation damage is one of the most spectacular and easily identified of the deleterious effects of cavitation, it is by no means the only one. Of at least equal—and possibly greater—importance is the effect of cavitation on the performance characteristics of hydraulic equipment. Broadly speaking, it can be said that hydraulic equipment consists of combinations of surfaces or passages which guide and constrain liquids to flow in specified directions at desired speeds. One effect of cavitation on such a surface or passage is to alter both the effective size of the passage and the direction of the guidance. There are very few cases indeed in which the flow under cavitating conditions conforms more closely to the designer's original intention than does the non-cavitating flow. In general, the flow pattern is degraded. The changes in direction are less than those specified, and the resistance to flow is increased. In centrifugal pumps these effects generally result in loss in head and often a simultaneous increase in power consumption. In hydraulic turbines the power output is lowered. In both cases the efficiency is reduced. Similarly, on ships' propellers, cavitation causes a reduction of the thrust and efficiency, and hence, of the speed of the ship. Fig. 2, Plate 1, is an example of tip cavitation on a model propeller. Cavitation on fins and rudders of surface and underwater craft causes loss of control and decrease of stabilizing effect.

The economic losses resulting from these decreases in performance and efficiency are numerous. Unfortunately, they are not as well recognized as those resulting from cavitation damage. Cavitation damage can cause a shut-down of a piece of equipment and necessitate immediate repair or replacement. It is easy to evaluate both the loss due to the shut-downs and the cost of repair. The events are isolated and conspicuous; hence the charges against them are clearly defined. The economic loss caused by the decrease in performance is less spectacular but much more insidious. Except in rare cases in which the amount of vibration or instability in operation is intolerable, the presence of cavitation interferes comparatively little with the operation of the machine. However, the economic loss due to the degradation of the performance accumulates every hour that the machine is in operation. Few comparative figures are available, but it is

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safe to say that the economic loss due to this decreased performance is many times that chargeable to cavitation damage. For example, the loss of 1 per cent of the efficiency of a 10,000 kW. turbine would be equivalent to a loss of about £1,000 per year, assuming the load factor to be relatively high. The existence of cavitation might easily cause a drop in efficiency or output of 3 per cent. Thus the yearly bill against cavitation for such a machine would be £3,000, in addition to the actual cost of repairs and the loss of revenue due to the out-of-service time.

Vibration Effects. The production of vibration in all types of hydraulic equipment is another effect resulting from cavitation. The cavitation process is an unsteady one and usually is associated with relatively large hydrodynamic forces. This produces vibration of the equipment in which the cavitation is occurring. The amplitude of the vibration may range from very small to large enough to cause major damage or even destruction.

Noise Produced by Cavitation. The cavitation process is essentially noisy. The importance of this noise varies tremendously with the use of the equipment. A given amount of cavitation noise in hydraulic machines in a large power house may be hardly detectable above the general noise level, which averages about 100 decibels. The same amount of noise, produced by a cavitating propeller on a submarine, may destroy completely the usefulness of the vessel.

This enumeration of the many deleterious effects of cavitation is intended to emphasize the importance of the phenomenon and the need for enough knowledge concerning it to enable the engineer to eliminate or at least control it.

DEFINITION OF CAVITATION

It has probably been noted that no attempt has been made as yet to describe or define cavitation. This is the normal state of affairs in this field since, even to engineers and scientists, cavitation is generally thought of and discussed in terms of its effects rather than in terms of the mechanics of the phenomenon. There is no intention to imply that little work has been done in this field. On the contrary, much time and effort have been spent in studying cavitation and its effects. Nevertheless, comparatively little definitive laboratory evidence has been accumulated concerning the detailed mechanics of the cavitation process. Some of the major reasons for this situation are: (1) the relatively high speed at which the phenomenon occurs creates major technical difficulties for the experimenter, particularly with respect to quantitative measurements; (2) it is becoming recognized that the characteristics of cavitation depend not only upon the hydrodynamics of the flow, but also on the physical properties of the liquid; (3) the extreme economic seriousness of cavitation damage has placed great emphasis upon the development of empirical methods of eliminating or controlling it. In the opinion of the author this economic pressure has had the effect of diverting considerable effort from the direct study of the cavitation phenomenon. It is also his opinion that it is necessary to have a sound understanding of the mechanics of cavitation on at least a semi-quantitative basis before significant progress can be made in developing rational design methods of controlling or eliminating it and of increasing the allowable performance limits of hydraulic machines and hydrodynamic processes.

It is now time to turn from consideration of the effects of cavitation to examination of the phenomenon itself. From the engineer's point of view, cavitation may be defined as the formation and collapse of cavities in a stream of flowing liquid which results from pressure changes within the stream caused by changes in the velocity of flow. A cavity may be expected to form at every point in the liquid where the local pressure is reduced to that of the vapour pressure of the liquid at the temperature of the stream. Collapse of such a cavity will start when the pressure in the surrounding liquid becomes greater than the vapour pressure, as, for example, if the cavity is transported by the liquid into a region of higher local pressure.

The formation of cavities is closely related to boiling. However, as far as the mechanics of the process is concerned, it is not necessary that the cavities be vapour-filled. They might con-

ceivably contain nothing or they might contain a gas, such as air, presumably at low pressure. One major difference between cavitation and boiling should be noted. In the boiling process heat is being added continuously to a liquid which is maintained at the vapour pressure in equilibrium with the existing temperature. Bubbles must form to absorb the added heat. If they did not form, the temperature of the liquid would increase. Thus boiling is essentially a thermodynamic process. In the cavitation process the thermodynamic condition is one of constant total heat, that is, no heat is added or taken away from the system. Usually the liquid is cold water or a similar fluid of low vapour pressure. Thus the pressure at which the cavities form is only slightly above absolute zero. If the cavity did not form and if the velocity level of the entire system were slightly increased, the local pressure would drop below absolute zero, that is, the liquid would have to sustain a tension. If a tension could not be sustained, the liquid would "break", thus forming a cavity. This cavity would then fill with vapour by evaporation of the adjacent liquid layer. During the cavity growth, the pressure would be slightly lower than the vapour pressure, as the heat of vaporization must come from the cooling of the surrounding liquid layer. Since the filling of the cavity is a secondary process, it will be seen that as far as the liquid is concerned, there is little difference between an empty cavity and one that is vapour-filled.

DESCRIPTION OF EXPERIMENTAL INVESTIGATIONS

Types of Experimental Equipment. Several different types of equipment have been developed for the study of the cavitation process*. Most of these fall into one of the following three classes: (1) equipment for studying single cavities; (2) Venturi-type flow channels; and (3) water tunnels.

Single-cavity Equipment. Single-cavity equipment is used to study only the collapse phase of cavitation. Reduced to its bare essentials, it consists of a closed container completely filled with liquid, provided with windows to permit observation and measurement. A diaphragm or bellows forms one part of the container. When this is extended mechanically, the added volume must appear in the form of a cavity. The experiment consists in releasing the diaphragm and observing the subsequent behaviour of the cavity. According to the definition just given, this cannot be considered true cavitation, since the changes in pressure are not caused by changes in the velocity of the flow. Indeed, there is no general flow in the experiment. The only liquid movement is associated with the change in volume of the cavity. The experimenter reasons that the method of cavity formation is unimportant, since he is concerned only with the collapse, and since at the beginning of the collapse the cavity is motionless with respect to the liquid. He considers that the pressure changes are the important factors, and that beyond producing these pressure changes the velocity of the fluid has nothing to do with the behaviour of the cavity.

There are several advantages of this type of equipment: the size and location of the cavity are under the control of the experimenter, the system pressure or even the rate of change in pressure can be made whatever is desired, and there is no flow velocity to interfere with the measurements. In addition, the equipment is comparatively inexpensive and small, and the cost of operation is negligible. The principal disadvantage is that the phenomenon under study is not true cavitation, but a simulation of it. Therefore, the validity of the results will be questioned until it can be proved definitely that the actual and simulated conditions are equivalent. It is probable that the greatest value of this type of experiment is to serve as a preliminary step to the actual experimental programme on true cavitation.

The Venturi Tube. One of the simplest pieces of equipment that can be used to produce cavitation is the Venturi tube. The liquid is accelerated from the entrance of the tube to the throat.

* This lecture will be limited to an examination of experimental findings concerning the mechanics of cavitation and their design implications. The mechanics of cavitation damage and the relative resistance of materials to such damage will not be considered; hence, no description will be given of such well-known equipment as the magnetostriction apparatus.

This produces the necessary drop in pressure for the development of a cavity. As the flow leaves the throat and enters the diffuser, deceleration begins, and the consequent increase in the pressure establishes the necessary conditions for cavity collapse. Furthermore, by controlling the system pressure it is possible to change the pressure level in the experimental section without affecting the velocity; thus cavitation can be induced or inhibited at will. Venturi tubes have been used to demonstrate cavitation in the classroom laboratory for many years. Research equipment using the same principle has also been constructed. In such equipment there is no question as to whether or not the real cavitation phenomenon is being studied. Furthermore, by inserting specimens of different materials in the walls, it is possible to study relative resistance to cavitation damage.

Experience has shown, however, that this type of equipment has inherent limitations. Many of them stem from the fact that the cavitation takes place on the channel walls. This means that the wall configuration determines the location and type of the cavitation. If it is desired to alter either, a major change in the equipment is necessary. In addition, since for convenience the Venturi tube is usually made symmetrical, the extent of the cavitation zone is relatively large compared to the size of the equipment. Therefore, if heavy cavitation is induced, the hydraulic properties of the flow circuit are modified seriously by the decrease in effective cross-section and increase in flow resistance caused by the presence of the cavitation voids. This situation has all the elements required to produce instability, that is, the increase in the resistance and decrease in effective cross-section caused by the cavitation alter the flow, which generally results in a decrease in velocity and an increase in pressure. This, in turn, reacts on the cavitation, tending to reduce it, thus eliminating part of the added resistance and constriction. Consequently, the flow accelerates, the cavitation zone grows, and the cycle restarts. The magnitude and frequency of the pulsations established by these conditions will be determined by the overall characteristics of the system, but they may well be so severe as to make observations impossible.

The Water Tunnel. The third type of equipment, the water tunnel, appears at first sight to be only a large Venturi tube. The main distinction seems to be that the water tunnel has a longer constant-diameter section at the throat. This is quite true. However, this simple change makes possible a completely different type of use. This constant-diameter section is christened the "working section", and various types of objects are supported in it for test. These test objects are made quite small as compared to the cross-section of the working area. In operation, the pressure in the working section is reduced only enough to produce cavitation on the test object, but not enough to produce it on the tunnel walls. Thus the relative amount of cavitation always remains small and has little or no effect on the characteristics of the flow circuit.

The elimination by the water tunnel of the disadvantages of the Venturi-tube test-equipment is not achieved without some sacrifice. The principal disadvantage of the tunnel is the relatively large increase in size and the consequent increase in cost of construction and operation. For example, consider a Venturi tube which is 2 inches in diameter at the throat. Since the cavitation occurs on the walls, the characteristic size of the test is the full diameter of the tunnel, that is, 2 inches. Assume that at the maximum throat velocity it requires a 5 h.p. motor to drive the circulating pump. Now compare this with a water tunnel of the proper size to test objects of diameter 2 inches with a reasonably low amount of interference from the walls of the tunnel. This will require a working section about 14 inches in diameter. If this is to be operated at the same velocity as the 2-inch tube, it will require about forty-eight times as much flow. If the two pieces of equipment have the same efficiency, the tunnel will require an input of 240 h.p. as compared with the 5 h.p. needed for the tube. Fortunately, a water tunnel is a versatile piece of equipment which can be used for many purposes other than the study of cavitation.

The High-speed Water Tunnel of the California Institute of Technology. Most of the experimental results to be discussed were obtained from tests carried out in the Hydrodynamics

Laboratory of the California Institute of Technology, principally in the high-speed water tunnel. Since water tunnels and the associated equipment used in cavitation tests are not very common, they will be described briefly. The two principal types of problem for which the tunnel was designed are: the determination of hydrodynamic forces on moving underwater bodies, and the investigation of various aspects of the cavitation phenomenon. The essential components of the tunnel are as follows:—

- (1) a working section in which the test object may be mounted and observed;
- (2) a circulating system consisting basically of a propeller-type pump and piping by which the flow of water may be maintained through the working section;
- (3) an air-content control system which maintains any desired concentration of dissolved air;
- (4) an absorption system which forces back into solution any air that may come out of the water during the cavitation test, thus maintaining the total air content undisturbed;
- (5) a cooling system which removes the energy added by the circulating pump and thus maintains a constant temperature;
- (6) a control system which maintains the pressure and velocity in the working section at any desired set of values;
- (7) a force-and-moment balance by means of which a test object may be supported in different positions in the flowing stream and measurements may be made of the hydrodynamic forces acting upon it.

The working section of this tunnel is 14 inches in diameter and has a usable length of 4 feet. It may be operated at any desired velocity up to 100 ft. per sec. and any pressure, from vapour pressure to 100 lb. per sq. in. A "closed" type of working section is used, because this design reduces the energy loss, increases the stability of the flow, and has other operating advantages. The working section has windows on both sides and the top, to facilitate visual observation and optical measurements. These windows are made of methylmethacrylate plastic (Perspex, Lucite). The inside surface is cylindrical and is carefully fitted to match exactly the walls of the working section. The outer surfaces are plane, to reduce the optical distortion which would otherwise result from looking into a cylinder of water. The effectiveness ratio, that is, the ratio of the amount of kinetic energy in the flow that passes through the working section in unit time to the power input, is about 5/1.

Fig. 3, Plate 2, shows the general appearance of this tunnel. The working section is on the upper level, to the right of the operator. Fig. 4 is an elevation of the tunnel, on which the flow circuit can be traced. The 48-inch propeller pump discharges vertically downward into the diffuser and pipe that carries the flow to the bottom of the absorption tank. Here the water reverses and flows upward, passing over the central partition and down again to the bottom of the absorption tank. There it enters the vertical pipe that carries it to the vaned elbow at the working-section level. The flow leaves the elbow in a horizontal direction, passes through a honeycomb and a settling, or quieting section, and thence through the nozzle into the working section. Screens may be inserted into the settling section to control the turbulence. The nozzle has an area reduction ratio of about 18/1, which results in a uniform velocity distribution and a thin boundary layer at the upstream end of the working section. Below the working section the flow enters the horizontal diffuser, in which the velocity is reduced to about one-third of that in the working section before it reaches the vaned elbow. Here the flow turns downward into a second diffuser, and then passes through two more vaned elbows and a horizontal run of piping to the inlet of the propeller pump. In a system of this design the pump operates under particularly advantageous conditions. The inlet pressure is high because the pump is located at the maximum available distance below the working section and the velocity is the minimum, since the diffusion has been completed. Furthermore, as the propeller rotates in the horizontal plane, the pressure is the same on all of the blades. This is not so for a horizontal-shaft installation. The resorber, named for its function of resorbing any free air bubbles, accomplishes its purpose by providing a container in which the water is main-

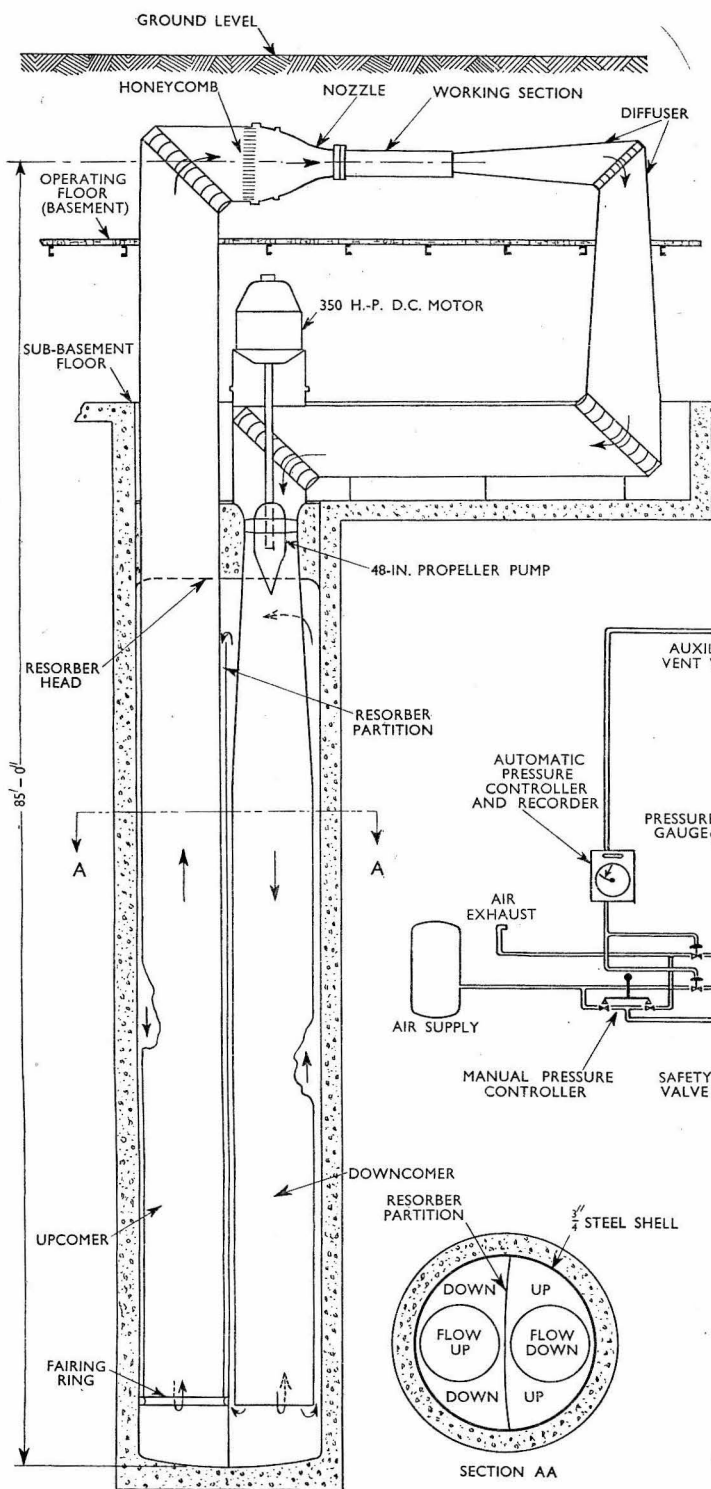


Fig. 4. Main Tunnel Circuit

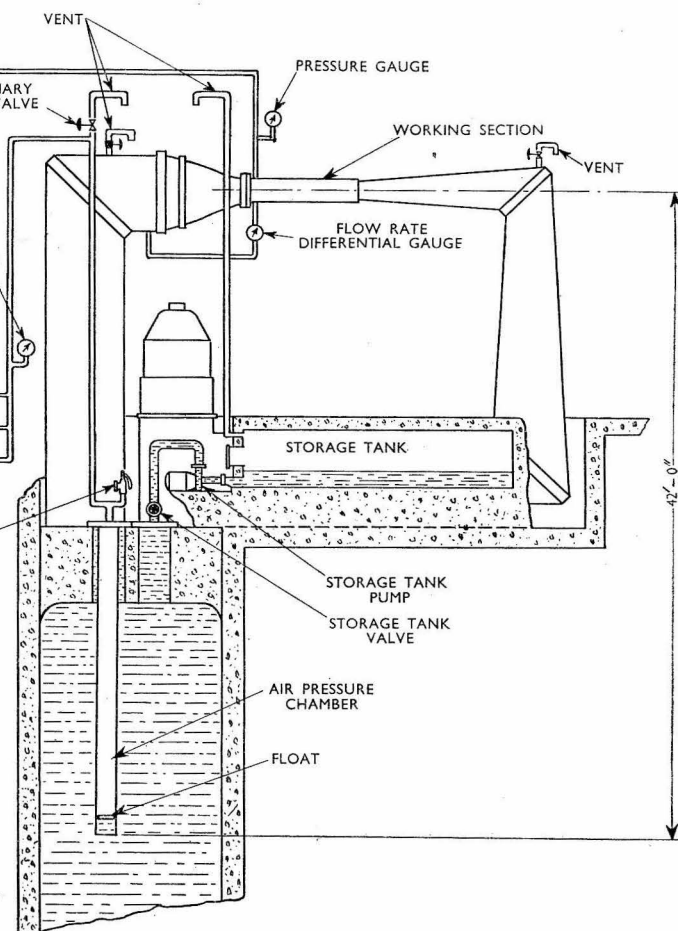


Fig. 5. Pressure Control Unit

tained for a relatively long time at a pressure which is considerably above atmospheric pressure under all conditions of operation.

A good pressure-control system is essential for cavitation studies. Fig. 5 shows the system used in this tunnel. Since the tunnel is closed and completely filled, the pressure of the working section may be controlled by control of the pressure at any point in the system. In this tunnel the control point is a small air

chamber in which the water level is approximately 40 feet below the centre-line of the working section. Owing to this difference in elevations, the air pressure in the control chamber is above atmospheric pressure at all times, even when the working section pressure approaches the vapour pressure.

The speed control system operates by holding constant the speed of the motor which drives the 48-inch pump. It is essentially a mechanical speed-matching system, in which the

speed of the drive-motor is constantly compared to that of a standard synchronous motor operating from a controlled-frequency power source. Even a minute difference in speed is automatically corrected so that the average speed of the drive motor is maintained at exactly the set value. The speed control unit, Fig. 6, Plate 3, contains a gear cluster with three selector gears which provide 1,000 steps of speed control.

High-speed Motion-picture Photography. The tool selected to record the physical details of the cavitation phenomenon is high-speed motion-picture photography. Motion pictures taken at one speed and projected at another can be considered as performing the function of either a time telescope or microscope. With this concept, the ratio of magnification is the ratio of the picture-taking speed to the projecting speed. For example, if pictures of a given phenomenon are taken at relatively long intervals and then projected at the normal cinema speed of 16 frames per sec., the times are apparently shortened in a manner comparable to that in which distances are apparently shortened when observed through a telescope. The telescope brings the distant object close enough to the observer for details of its structure to be observed; the "speeded-up" projection of the pictures brings the time details of the phenomenon close enough together for them to be observed. Conversely, motion pictures taken at a high rate of speed and projected at a much lower rate of speed serve as a time microscope, since the process resolves the details in time in the same manner as the microscope resolves the details in space.

Equipment such as this is needed to change the time scale for exactly the same reason that telescopes and microscopes are needed to change the length scale. The human senses and brain have limited ranges in which they can get an undistorted concept of what is occurring. Therefore it is necessary to transform the actual times and distances involved in a given phenomenon until they fall within these limited ranges. In the Hydrodynamics Laboratory pictures of cavitation have been taken at rates varying from 64 to 20,000 frames per sec. When these are projected at the normal viewing rate of 16 frames per sec., time magnifications of from $4/1$ to $1,250/1$ are secured.

Description of Photographic Equipment. Photographic equipment used in this study is of the multi-flash type. The pioneering development in this field was carried out by Professor Harold E. Edgerton and his associates at the Massachusetts Institute of Technology. The system consists of a simple camera in which the recording film moves through the focal plane at a high constant speed. The camera has no mechanical shutter. The required illumination is provided by synchronized flash lamps which also act as the camera shutter.

The camera is the standard General Radio instrument, shown in Fig. 7, Plate 3, adapted for use with a series of lenses of varying focal lengths. The commutator provided on the film drum to synchronize the flashes with the film travel is not used; instead, the pulsing of the flash lamps is controlled by an oscillator.

The Laboratory has carried out considerable work to increase the flash rate of the lamps. The original equipment operated satisfactorily at 3,000 flashes per sec. This limitation was found to be in the control circuit. To increase the maximum picture-taking rate, the Laboratory developed a system in which several control circuits are synchronized through a multi-phase oscillator to discharge their energy pulses in rotation through a single lamp. With this system the flash rate is that of a single control circuit multiplied by the number of circuits involved. Thus far a maximum of six circuits has been used and pictures have been taken at the rate of 30,000 flashes per sec.

In the use of such a combined camera and flash-lamp system the characteristics of the flash lamps exert a controlling influence upon the work that can be done. The most important characteristics of the flash lamp are the effective duration and the brilliance of the flash. The flash duration depends on the tube design, the pressure and composition of the gas used in it, and the energy input per flash. For the flash tubes used in this work the effective flash duration is about 2 microseconds, with an input of 1 joule per flash. For critically sharp results, the maximum usable film speed is fixed by the criterion that the allowable motion of the image on the film during one flash should be equal

to the diameter of the circle of confusion of the lens. For extremely high-speed work it may be necessary to accept somewhat greater blurring, and the corresponding loss of accuracy.

A simple example will illustrate the severity of the restrictions imposed upon high-speed motion picture photography by the flash duration and the sharpness requirements. Assume a flash duration of 2 microseconds and an allowable circle of confusion of 0.0025 inch diameter. Under these conditions the maximum permissible velocity of the image on the film is the quotient of the circle of confusion divided by the flash duration. This is 1,250 in. per sec., or about 104 ft. per sec. Assume cavitation pictures are being taken at a tunnel velocity of 100 ft. per sec. and that the camera is so located that the image size is one-sixth that of the object. The corresponding image velocity is about 17 ft. per sec. Under normal conditions this velocity is at right angles to the film travel. The solution of the velocity vector triangle gives a maximum permissible film velocity of slightly over 100 ft. per sec. If a picture-taking rate of 20,000 frames per sec. is required, the maximum permissible frame height is $\frac{1}{16}$ inch, which means that the experimenter must be satisfied with a long and very narrow picture. This calculation also shows that in nearly all cases the film speed is the governing factor and that, unless the object being photographed is moving very rapidly, its speed may safely be ignored.

The light intensity of the flash must be very high to produce an image of reasonable density in the very short exposure time available. This is illustrated by another hypothetical example. Imagine a motion-picture camera of the standard type, using a normal shutter but operating at 20,000 exposures per second. Such a shutter has an effective exposure time of about one-half of the time that has elapsed between successive pictures. In this case the exposure would be $\frac{1}{40,000}$ second as compared to $\frac{1}{40}$ second for a normal motion-picture camera. Thus a thousandfold increase in the intensity of illumination would be required if an equal exposure were to be secured. However, $\frac{1}{40,000}$ second is 12.5 times as long as the duration of the flash. Hence the intensity of the flash must be 12,500 times as bright as a light source which would be adequate for a motion-picture camera photographing the same object at the normal rate of 16 frames per sec. The flash-lamp system requires a continuous input of 20 kW.; however, as the lamp is burning only one-twenty-fifth of the total time, the energy input to it during the exposure is at the rate of 500 kW.

The flash lamp used is a small straight quartz tube about 8 inches long and $\frac{1}{4}$ inch in diameter. This is mounted in a cylindrical reflector having an elliptical cross-section of proper dimensions to concentrate the light in a fairly narrow band on the body under test. Fig. 8, Plate 3, shows the appearance of the working section during the taking of these high-speed photographs.

Supplementary Experiments. Supplementary experiments were carried out in conjunction with the high-speed photographs of the cavitation process. Measurements were made of the pressure distribution on the surfaces of the test bodies when operating both under non-cavitating and cavitating conditions. For this purpose special models were constructed in which a series of piezometer openings was provided. These openings were connected by means of tubes of very small diameter to pressure-measuring equipment on the outside of the tunnel. Some tests of these were made in the Hydrodynamics Laboratory. A more complete series was carried out in the water tunnel at the State University of Iowa (Rouse and McNown 1948). A few measurements were made of the effect of cavitation on the drag or resistance force by mounting the body on the spindle of the balance, and measuring the drag force directly. This procedure was not so simple because of the severe vibrations induced by the cavitation. Thus these measurements were not as satisfactory as could be desired.

EXPERIMENTAL RESULTS AND CONCLUSIONS

Definition of Cavitation Parameter. In the discussion of all types of cavitation problem, experimental results, and performance of equipment, some system of describing quantitatively the dynamic conditions under which the cavitation is taking place

immediately becomes necessary. Fortunately, such a system has won universal acceptance. It involves the use of a dimensionless quantity called the cavitation parameter, and is given by

$$K = \frac{p_L - p_B}{\rho \frac{V^2}{2}} = \frac{h_L - h_B}{\frac{V^2}{2g}}$$

where (in consistent units) p_L and h_L are the pressure and pressure head in the undisturbed liquid, p_B and h_B are the vapour pressure and pressure head corresponding to the liquid temperature, V is the relative velocity between the body and the liquid, normally measured where the liquid is undisturbed, ρ is the liquid density, and g is the acceleration due to gravity.

Physical Significance and Uses of Cavitation Parameter. The physical significance of this parameter is clear. The numerator is the net pressure or head which acts to collapse the cavity. The denominator is the velocity pressure or head of the flow. Now the variations in pressure which take place on the surface of the body or on any type of guide passage, are due basically to changes in the velocity of the flow. Thus the velocity head may be considered as a measure of the pressure reductions that may occur to cause a cavity to form or expand. From this point of view the cavitation parameter is simply the ratio of the pressure available for collapsing the cavity to the pressure available for inducing the formation and growth of the cavity. It transpires that this parameter, K , is a very useful measure for many different aspects of the cavitation phenomenon. For example, if the first traces of cavitation appear when $K = K_i$ (incipient cavitation), K_i can be interpreted as the maximum reduction in pressure on the guiding surface, measured in terms of the velocity head. Thus, if $K_i = 1$, the lowest pressure at any point on the surface is one velocity head below that of the undisturbed flow. It follows directly that K can be used to designate the relative cavitation resistance of a given nose shape or an entire piece of hydraulic equipment. This is accomplished by assigning to the object its measured value of K_i . The lower this value, the higher is the object's resistance to cavitation.

Many similar uses are found for this parameter, some of which will be discussed later. Therefore, it is always necessary to specify the use which is being made of K in each particular case, as for example, K for incipient cavitation, K for a fully developed cavity, K that characterizes the flow conditions, etc. In this connexion one very convenient use is for the comparison of the condition of the flow with the cavitation resistance of the object. For example, consider a centrifugal pump installation. Assume that for the best available pump for this installation $K_i = 0.4$, measured at the inlet. This means that the user must install the pump at an elevation low enough for the K value of the flow entering the pump never to be less than 0.4. If he is able to do this, then he can be sure of cavitation-free operation. If not, then cavitation can be expected to occur at all times when the K value of the flow drops below 0.4. It will be noted that the value of K varies if either the pressure or the velocity is changed. This is particularly important when K is used to define the character of the flow. Thus the K value of the tunnel working-section may be varied over wide limits by simply varying the pressure level while the velocity remains constant.

Inception and Life History of a Cavity. The high-speed motion-picture technique makes it possible to trace in considerable detail the life history of a cavity, from its inception to its final disappearance. Fig. 9, Plate 4, shows a strip of pictures, taken at the rate of 20,000 frames per second. The portion of the test body seen is a very narrow band along the top. The cavities are practically in silhouette. Each horizontal line represents an individual photograph. The total length of time covered by this entire strip, which is seen in two sections, is about 0.006 second. A line drawing of the test body is seen just above each strip. It is drawn to the same scale as that of the photograph. The relative location of the cavity on the body is obtained by projecting any individual picture vertically upward on to the diagram. The test body is a cylinder with a pointed nose. The radius of curvature of the nose is 1.5 times the diameter of the cylinder, and is commonly referred to as a 1.5 calibre ogive. The tunnel was

operated at 40 ft. per sec., and the absolute pressure in the undisturbed flow was about 4 lb. per sq. in. This is equivalent to $K = 0.33$.

These pictures proved to be sufficiently sharp and clear to permit measurement of cavity diameters. The cavity indicated by the arrow was selected for study. It appears first as a smooth transparent bubble which has a relatively slow growth and a much more rapid collapse. After complete collapse it reappears, this time with a rough, irregular wall. Nevertheless, the growth and collapse cycle is repeated. A third cycle follows, and then a fourth, fifth, and sixth, each successive one being smaller. Measurements were made of this cavity on each frame. The average cavity radius was assumed to be one-half of the mean of the horizontal and vertical dimensions as measured in Fig. 9. Fig. 10 shows a plot of these measurements. The convention

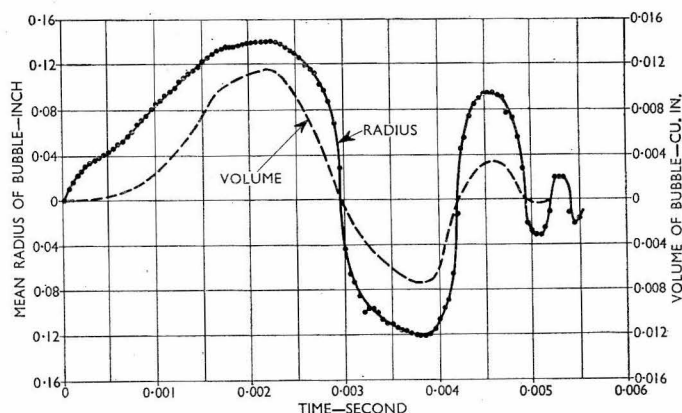
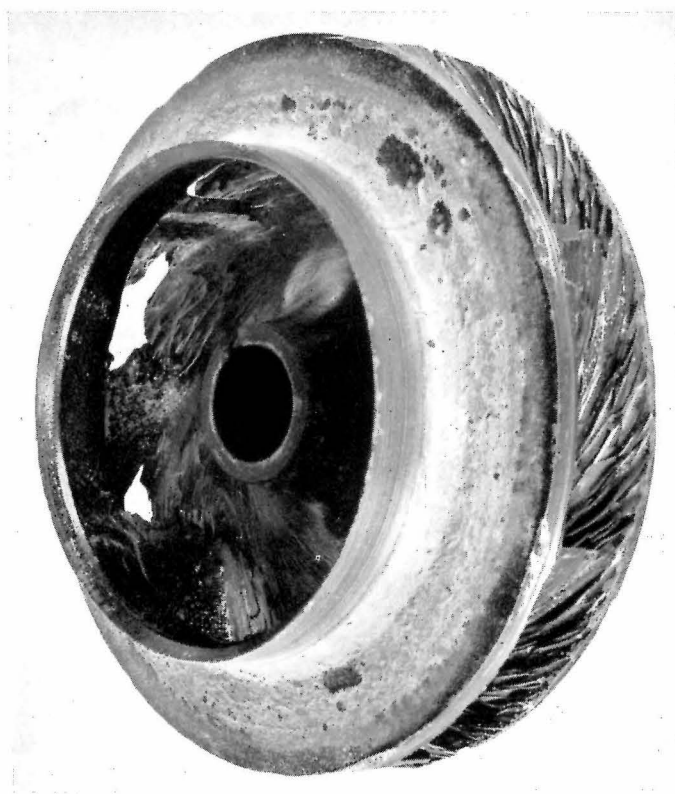


Fig. 10. Time-Radius Curves of Bubble

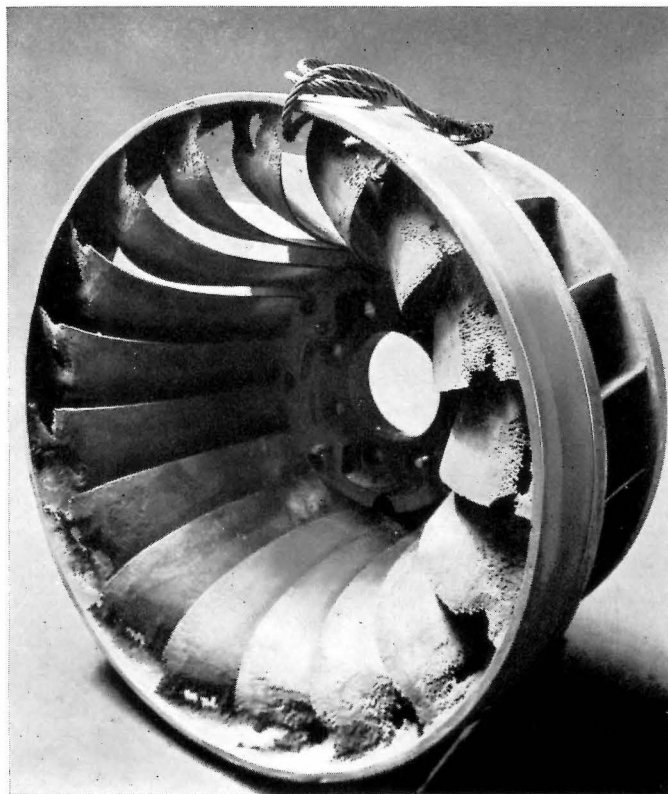
used is that the history of the first growth and collapse is plotted above the zero line, the second appearance, that is, the first rebound, below the line, the next above, the next below, and so on. The reason for this is to simplify the determination of the time of complete collapse and to avoid confusion between the last stages of collapse and the first stages of rebound. The dotted line shows the volume history on the assumption that the cavity is a sphere.

Details of Cavity History. It is possible to obtain considerable insight into the mechanics of this process by examining in detail the life history of this one cavity, which is typical for at least one important type of cavitation. Fig. 11 will assist in this study. At the top will be seen the half-profile of the test body. The graph below it, drawn to the same longitudinal scale, shows the pressure distribution on the surface of the body and the behaviour of the cavity from its inception to its first collapse. It will be noted that only the negative portion of the pressure distribution curve is shown. The ordinate for this curve is absolute pressure. The vapour pressure of the water, at the temperature of the experiment, is shown by the horizontal dashed line. The pressure distribution is that measured for non-cavitating conditions, that is, for a high value of K . The dotted line having the horizontal section A-B shows the changed pressure distribution for $K = 0.33$. The curves showing the radius and volume of the cavity are the same as those seen in Fig. 10 with the exception that the abscissa is distance, measured along the test body, instead of time.

Point A shows the position on the nose of the body at which the pressure has been reduced to the vapour pressure of the water. It will be seen that this is also very nearly the position at which the cavity is first detectable as a tiny bubble. Fig. 9 shows that the cavity moves downstream on the body. As seen from Fig. 11, it is moving into a region in which the pressure tends to decrease below the vapour pressure. Therefore, it is not surprising to observe that the cavity grows at a rapid rate. This high rate of growth continues nearly to point B, which corresponds to the position on the body at which the pressure climbs up back to vapour pressure.



a Small pump impeller.



b Francis turbine runner.

Fig. 1. Severe Cavitation Damage

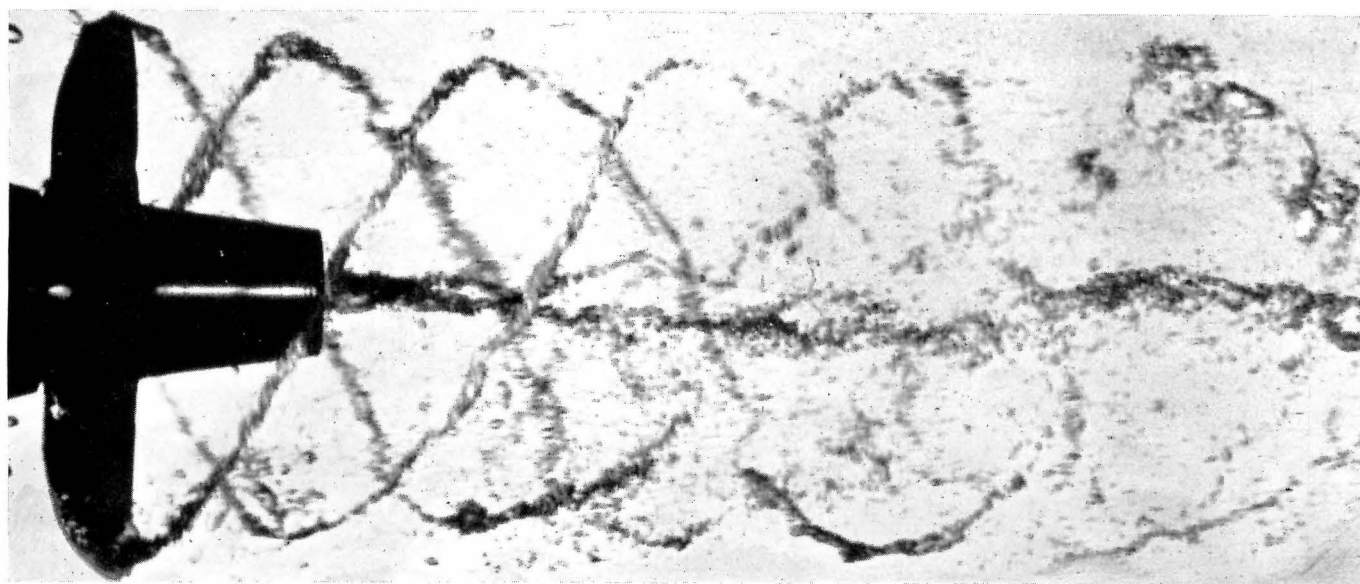


Fig. 2. Tip Cavitation

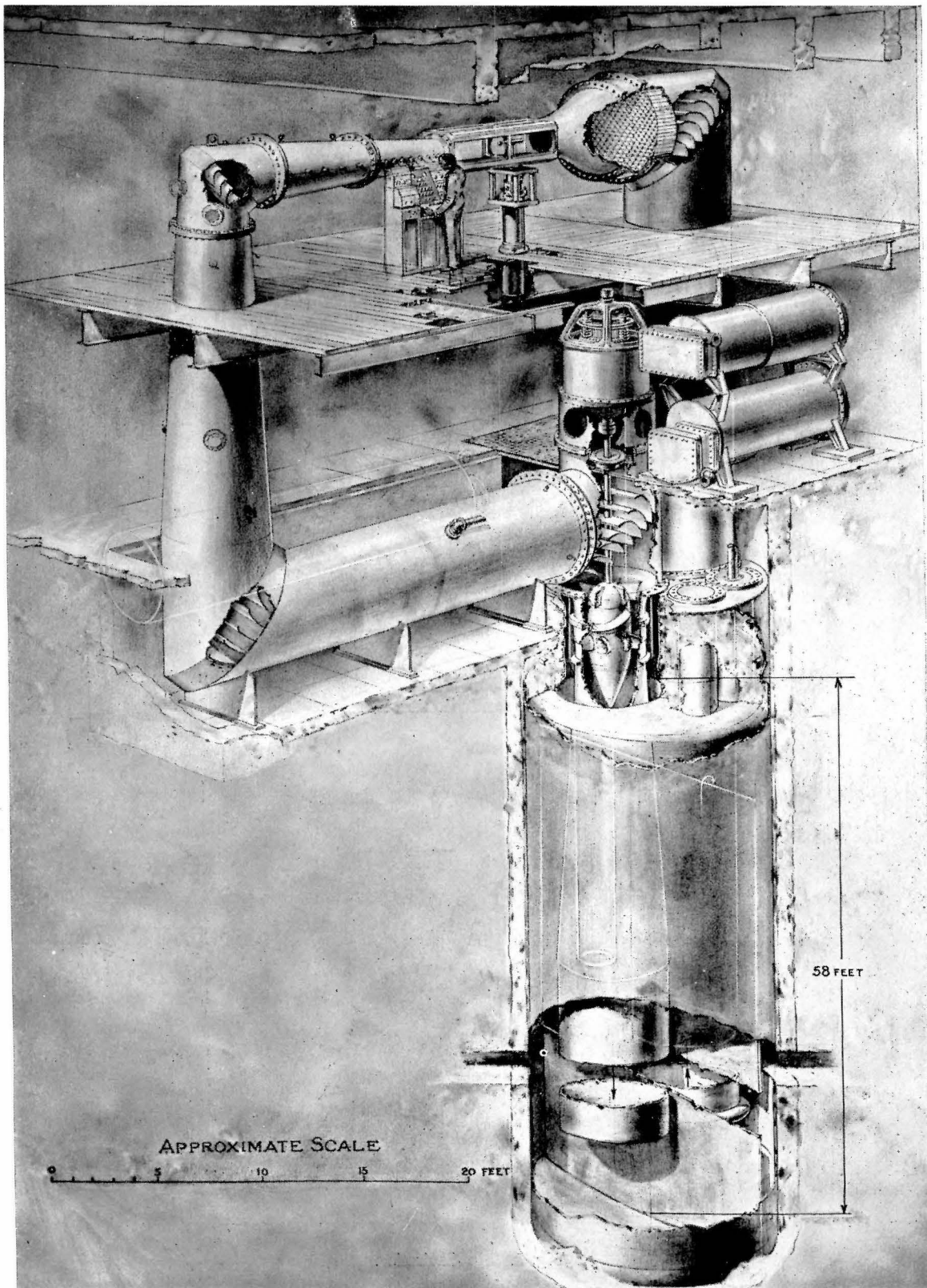


Fig. 3. High-speed Water Tunnel

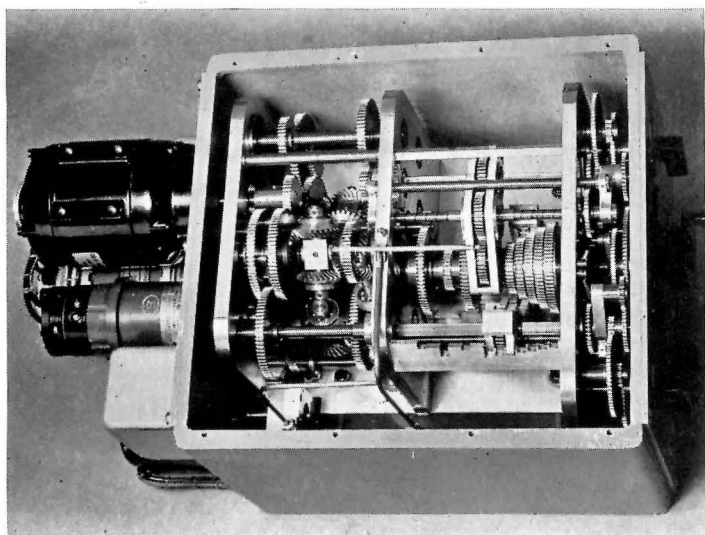
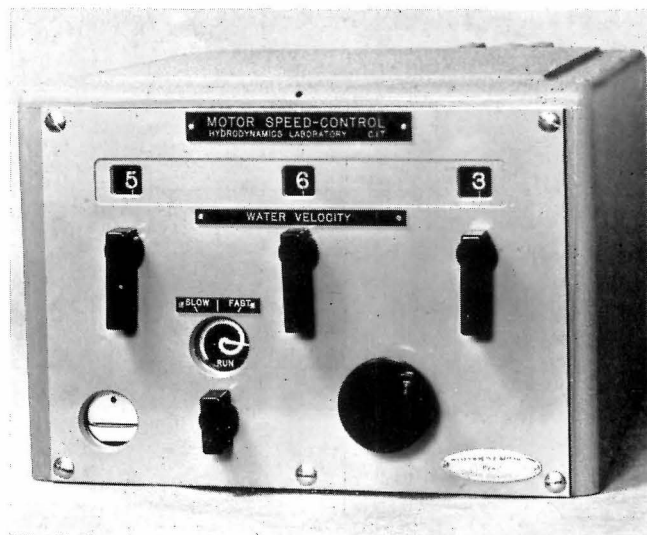
*a* Open.*b* Closed.

Fig. 6. Speed Control Unit

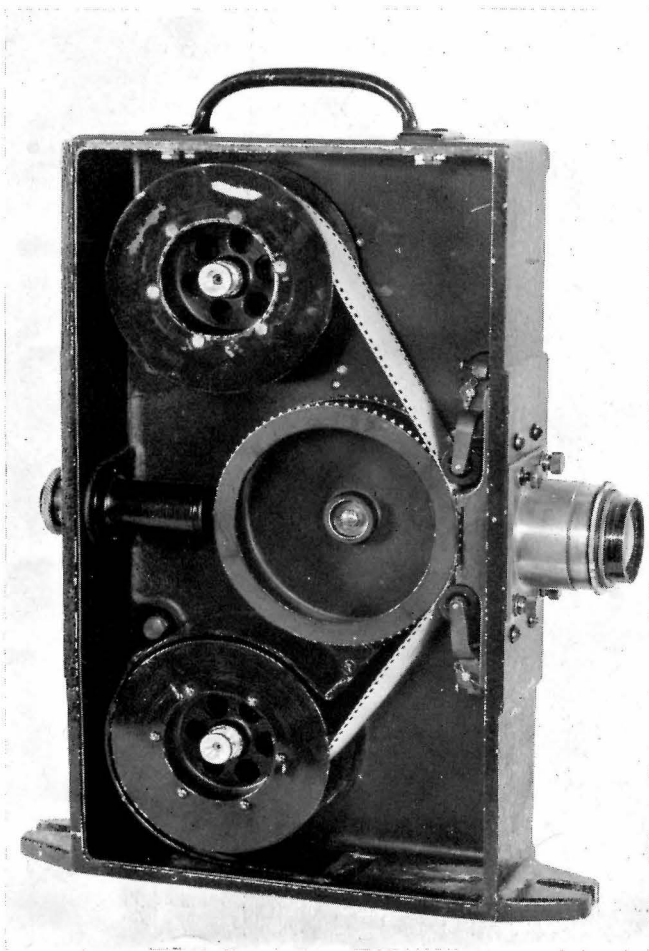


Fig. 7. High-speed Motion-picture Camera

[I.Mech.E., 1952]

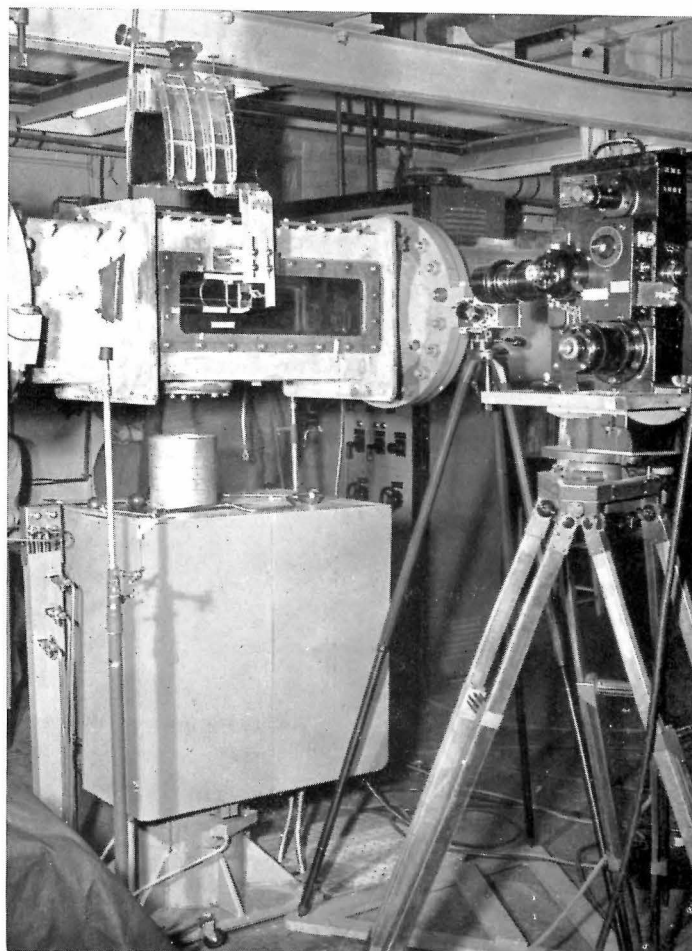


Fig. 8. Tunnel Working Section with High-speed Photographic Equipment

The elliptical reflector of the flash lamp is mounted above the working section.

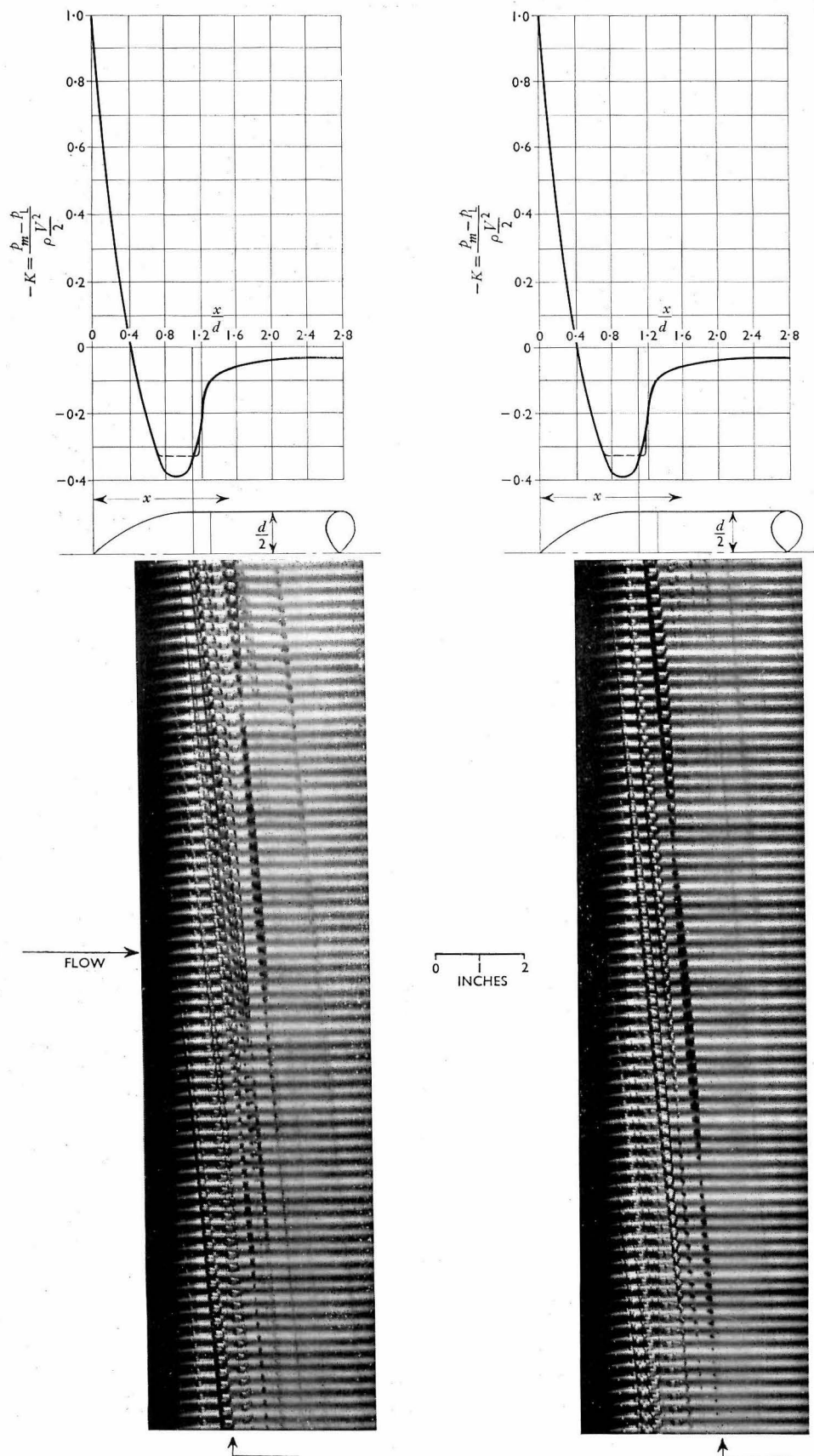
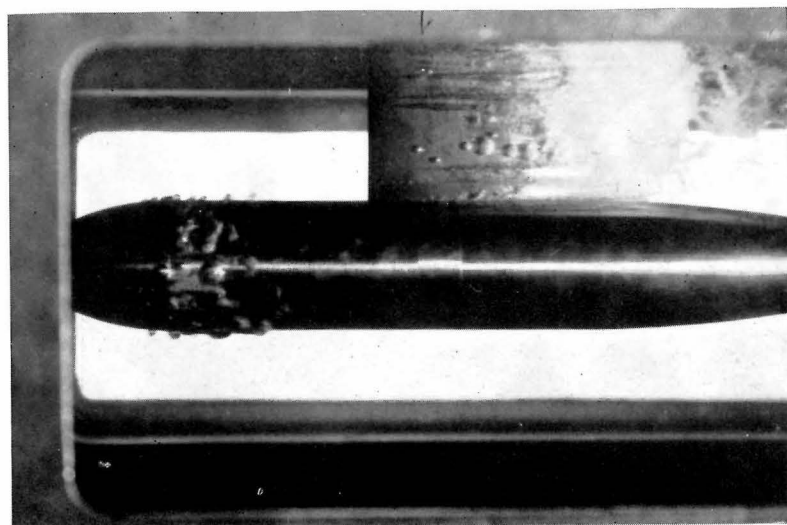
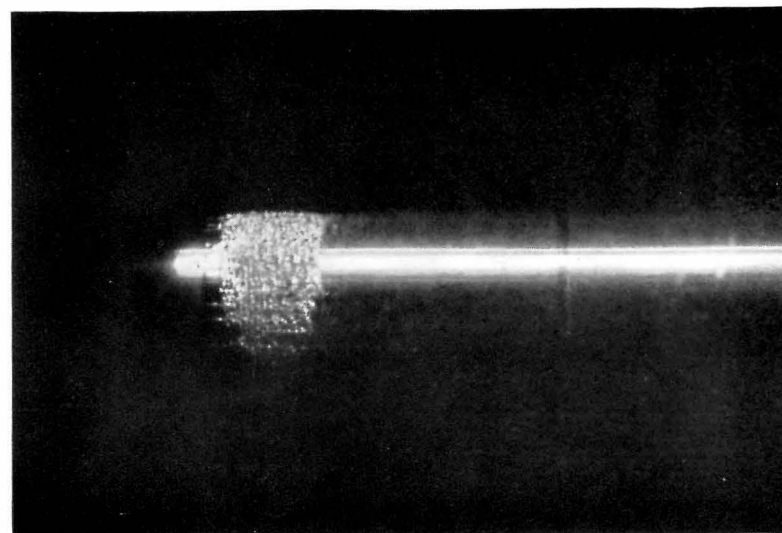


Fig. 9. Life History of Cavitation Bubble
 p_m Measured pressure on the surface of the body

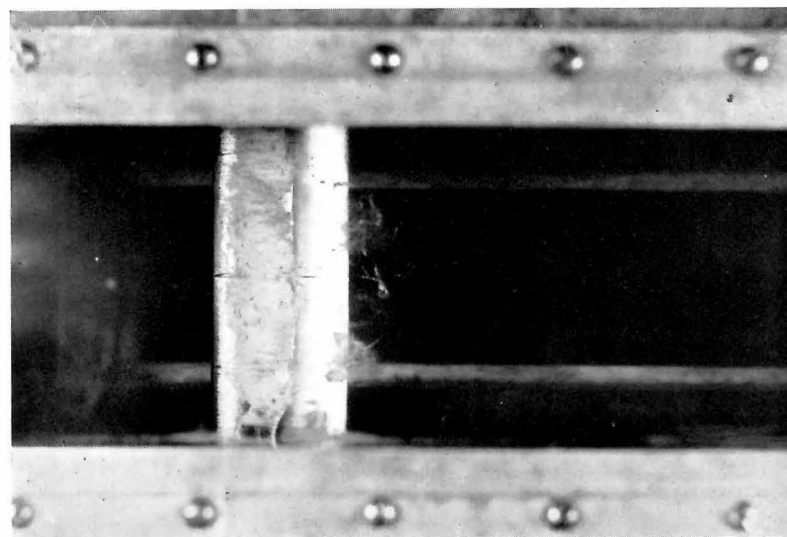


a Travelling cavities, $K = 0.26$.

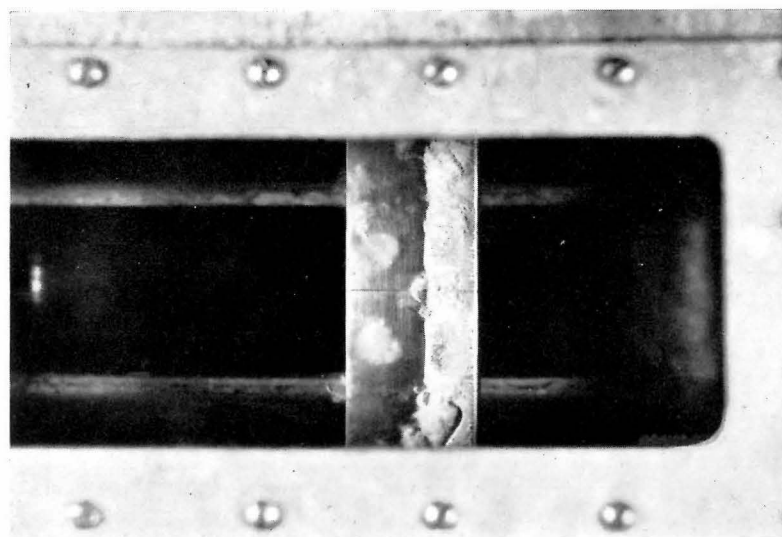


b Fixed cavity, $K = 0.27$.

Fig. 12. Light Cavitation on 1.5-inch Calibre Ogive

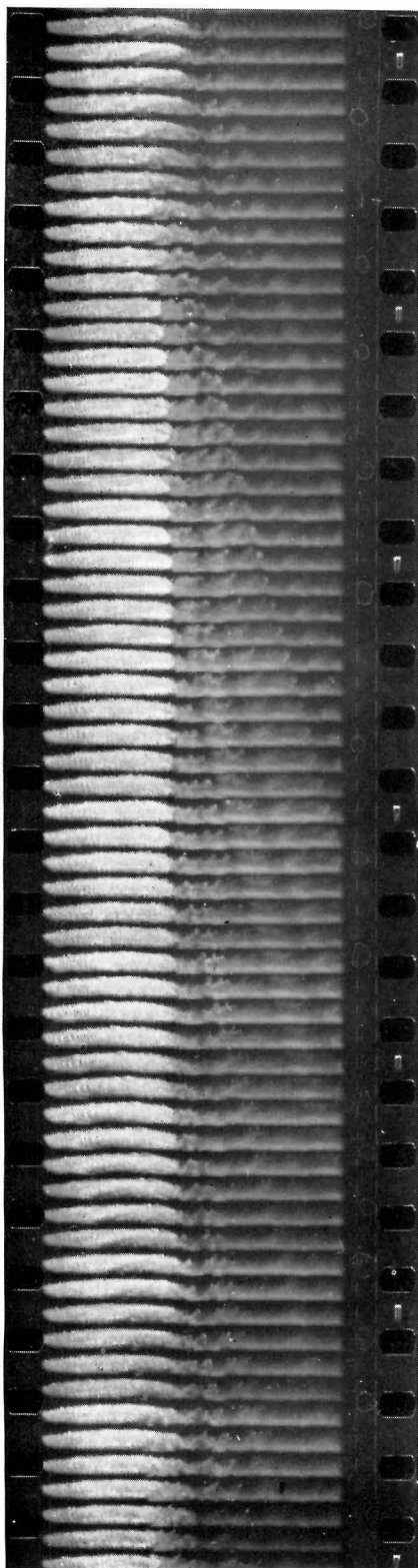


a Upper surface, $K = 1.36$.



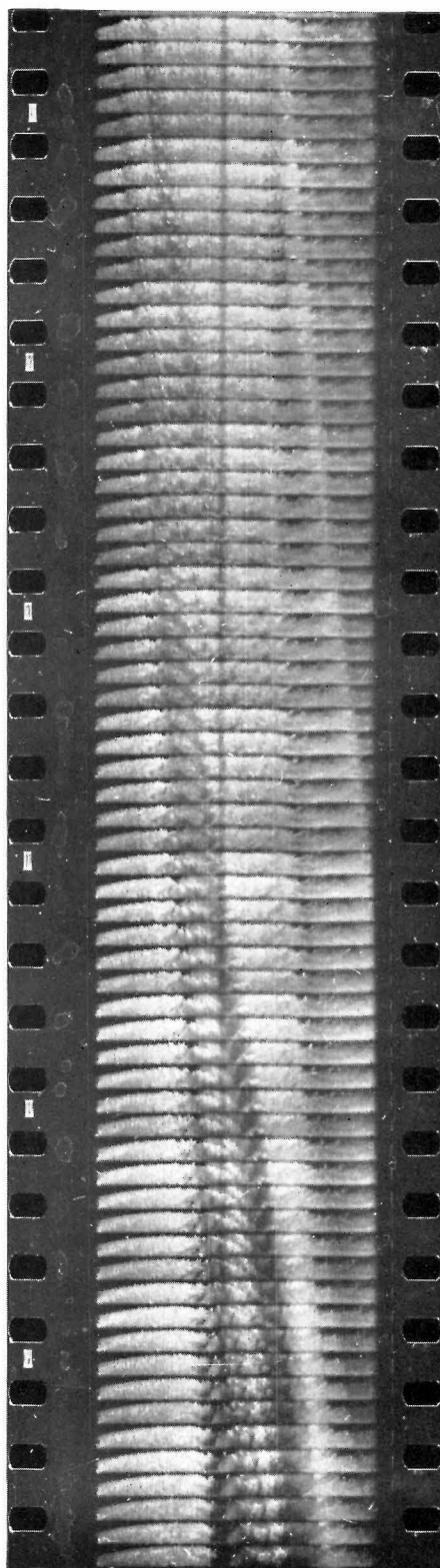
b Lower surface, $K = 0.82$.

Fig. 13. Entrainment from Fixed Cavity on Surfaces of Hydrofoil



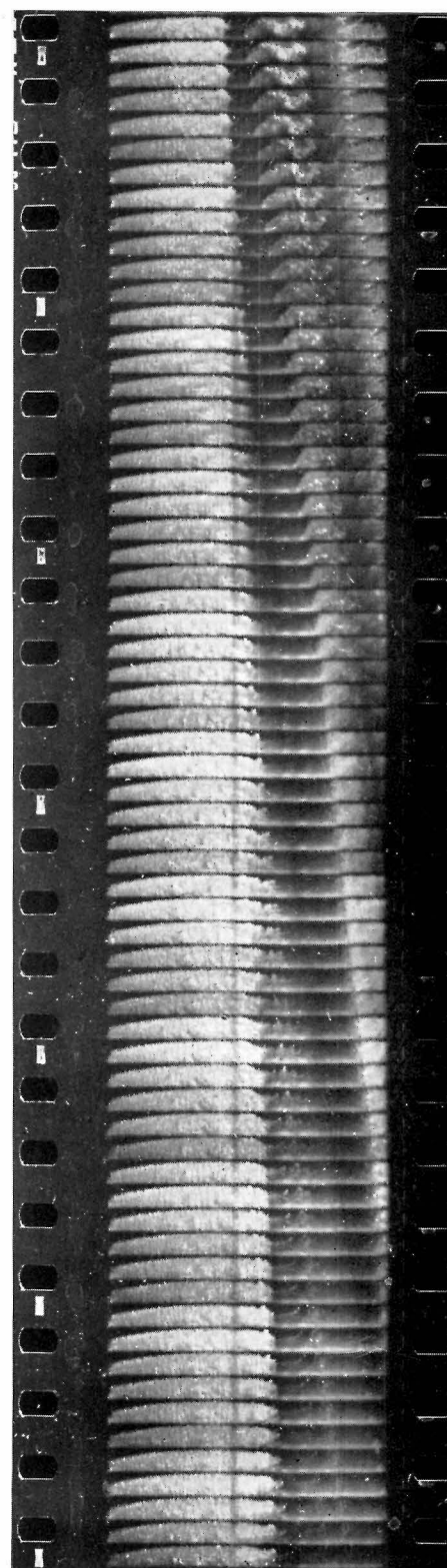
a

a 1.5-inch calibre nose:
 $K = 0.25$, $V = 96$ ft. per sec.

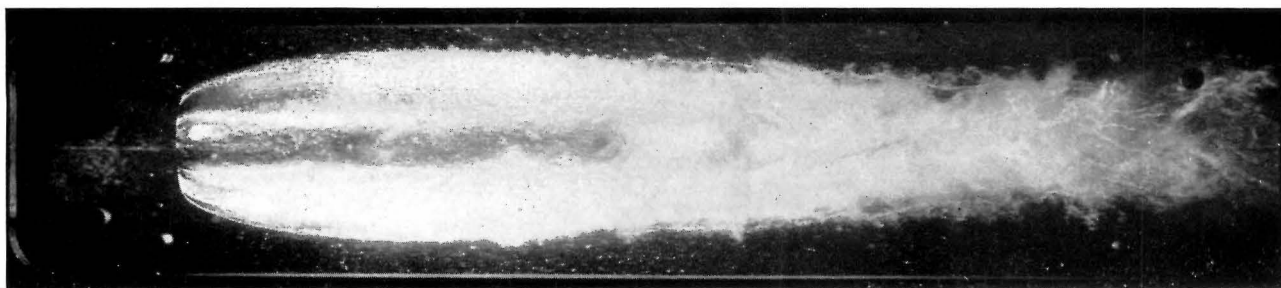


b

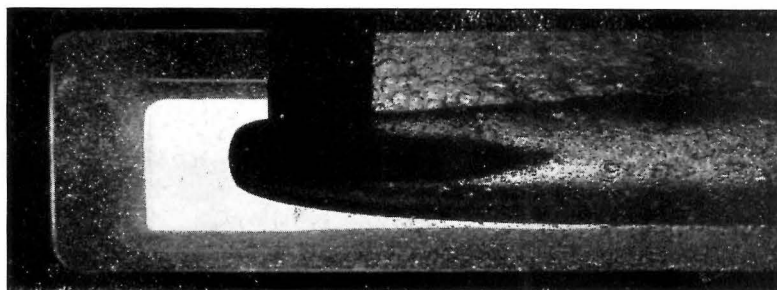
b Hemispherical nose:
 $K = 0.37$, $V = 50$ ft. per sec.



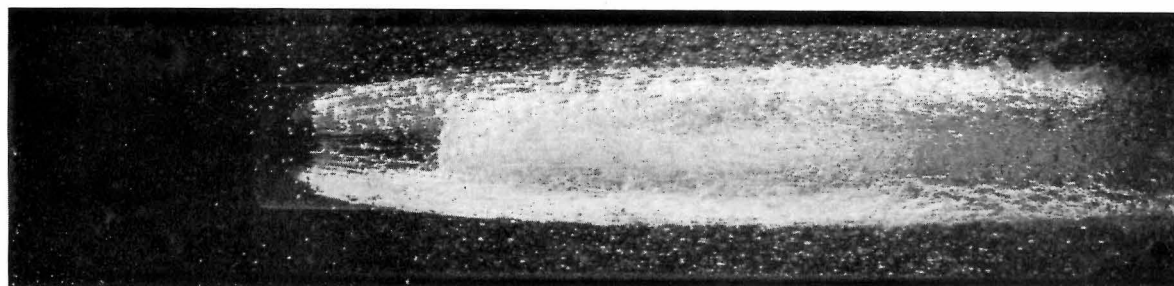
b contd.



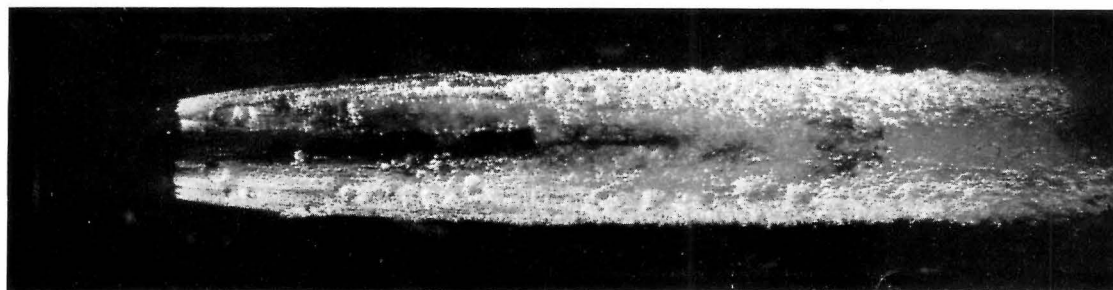
a Square-ended cylinder, $K = 0.55$.



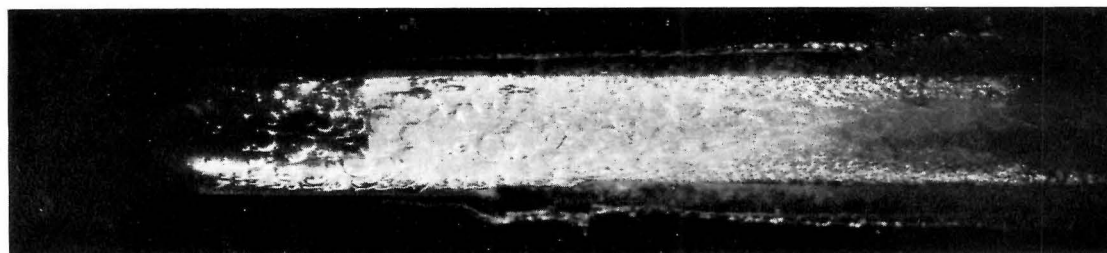
b Blunt ellipse, $K = 0.44$.



c Hemisphere, $K = 0.28$.

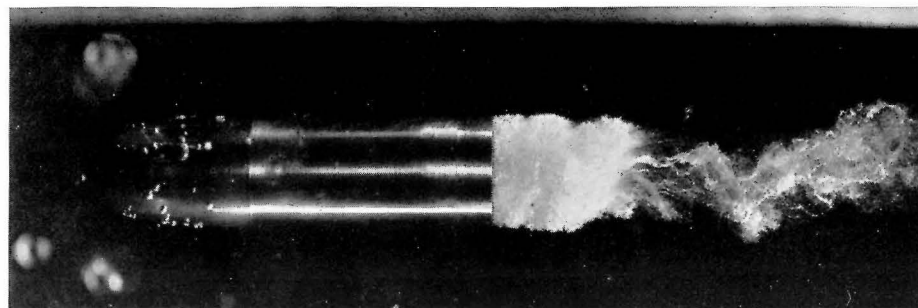


d 1 calibre sphereogive, $K = 0.21$.

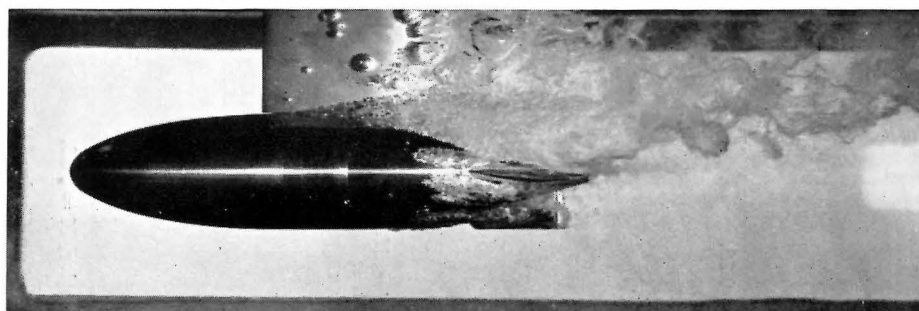


e 2.5 calibre sphereogive, $K = 0.23$.

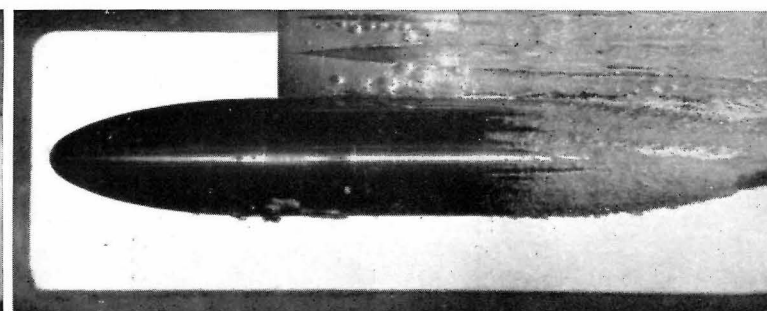
Fig. 19. Effect of Nose Shape on Cavity Diameter



a Square-ended cylinder, $K = 0.29$.



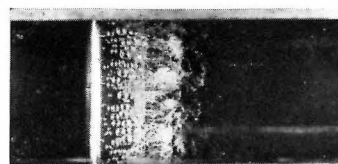
b Special curve, $K = 0.20$.



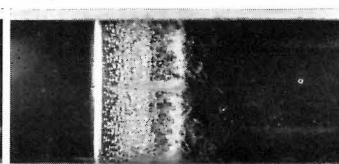
c Special curve, $K = 0.18$.

Fig. 21. Cavity on Afterbody

Angle of attack
-4 deg. 0 deg. +4 deg. +8 deg. +12 deg.

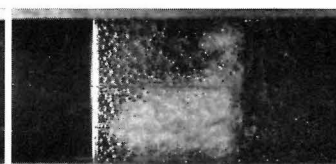


$K = 0.30$.

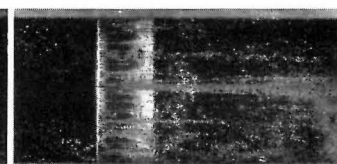


$K = 0.30$.

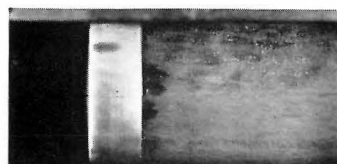
Upper surface.



$K = 0.27$.

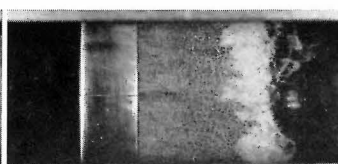


$K = 0.29$.



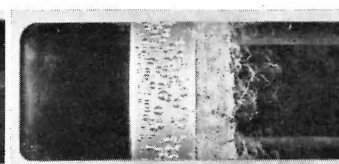
$K = 0.26$.

a



$K = 0.26$.

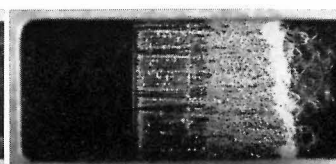
b



$K = 0.26$.

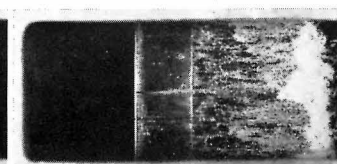
Lower surface.

c



$K = 0.29$.

d



$K = 0.30$.

e

Fig. 22. Effect on Cavitation of Variations in Angle of Attack for Hydrofoil N.A.C.A.-4412

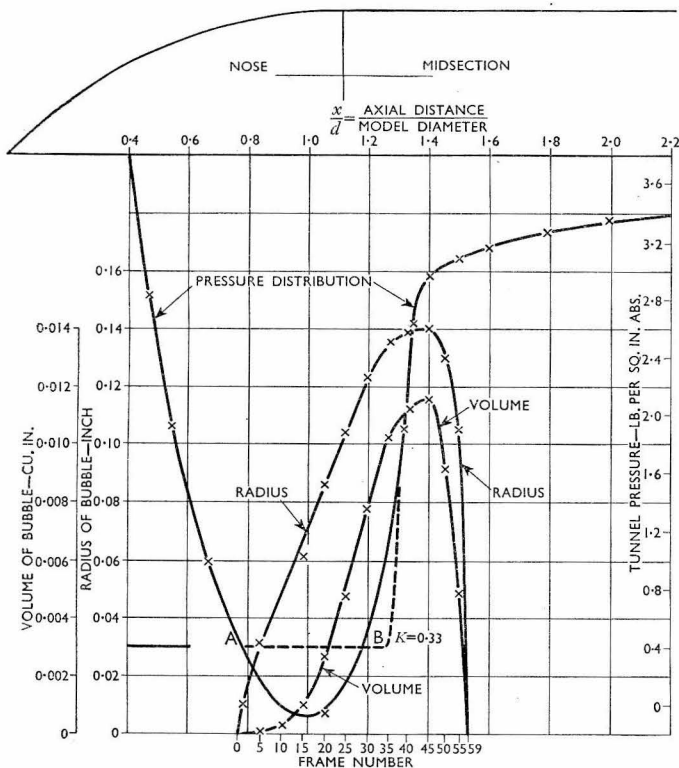


Fig. 11. Relation of Bubble Growth and Collapse to Pressure

Cavity Hydrodynamics. It must be remembered that references to the behaviour of the cavity and the motion of the cavity wall are really only figures of speech. So far as the dynamics of the system are concerned, the cavity is nothing but an empty space surrounded by the liquid. What is seen, and what is important, is the motion of the free surface of the liquid. Thus during the rapid growth of the cavity the liquid is moving radially outward at a high speed. From points A-B, this outward radial flow is taking place in the direction of the pressure gradient. From point B onward, it is against the pressure gradient. Thus, as the curves for both radius and volume show, this motion is decelerated, and finally ceases at the point of maximum radius. The cavity radius then begins to shrink at a rate that indicates a high radially inward acceleration. This is confirmed by reference to the pressure diagram. If it is assumed that the pressure inside the cavity is the vapour pressure, there is a pressure difference of approximately 2.5 lb. per sq. in. acting to produce this acceleration. It will be recognized that this pressure difference is the numerator of the cavitation parameter. Viewed with respect to the pressure distribution diagram, the behaviour of the cavity is very rational; indeed, it could have been predicted from Newton's laws of motion. On the other hand, such a prediction requires a knowledge of the pressure distribution diagram.

The question might well be asked as to the physical explanation of the pressure variation on the body. It is not difficult at this point to become confused as to whether the motion of the liquid produces the pressure variations on the body or whether the pressure variations on the body cause the motion of the liquid. Such confusion is largely a confusion of terms. Any fluid particle may be considered as a free mass with an associated force system. Consider such a particle of liquid in the flow which impinges on the nose of the body near the point and follows along the surface. Since the particle cannot penetrate the surface of the body, it has to move laterally to get around it. To move laterally, however, the particle must shove other particles out of the way. The effect of these collisions, combined with force applied by the body to prevent the liquid from passing through its surface, is manifested in the pressure field that develops.

The lateral outward acceleration of the original particle continues until it and all of the adjacent particles are moving parallel to the body surface. It will be found that when this state is reached, the pressure on the surface has decreased until it is equal to the static pressure in the undisturbed flow, that is, the particles have acquired a lateral component of motion high enough to keep them out of the way of the body. Downstream from this point the surface of the body curves away from this tangential path. This takes away the constraint on the side of the particle next to the body, that is, the force acting between the particle and the body is reduced. The resulting unbalance of the force system causes the particle to accelerate toward the body, along a curved path. If the surface of the body falls away from this path so rapidly that all constraint on the particle is removed, then the pressure between the body and the particle is zero. The minimum radius of curvature of the particle in this case will be determined by the free stream pressure. If the body falls away from the path of the particle even more rapidly than this, there are two possibilities: either a tension force must be set up between the surface of the body and the particle, to constrain the particle to follow the curvature of the body, or else the particle will leave the body surface. In the latter case a cavity must form.

Thus it is seen that cavitation will take place only in regions in which the guiding surface is curving away from the local direction of flow. Whether or not cavitation actually takes place will be determined by whether the radius of curvature of the surface at the point under consideration is greater or less than the minimum radius of curvature of the filament of liquid next to the surface, if the pressure on the concave side of this filament is assumed to be vapour pressure. If the surface radius of curvature is greater than the minimum filament radius, no cavitation will occur. If it is less, then cavitation takes place, that is, the liquid flow breaks away and produces voids*. The salient features of this cavitation process are:—

- (1) the cavity starts to form at the point on the guiding surface where the pressure is reduced to vapour pressure;
- (2) cavity growth continues as long as the surface pressure is at or below vapour pressure;
- (3) as the pressure on the surface increases until it is again above vapour pressure, the rate of cavity growth decelerates; the cavity quickly reaches the maximum size, and immediately starts to collapse;
- (4) the collapse rate is much higher than that of formation.

Cavitation Types. Fig. 12, Plate 5, shows two single-flash pictures both taken of the same test body but at slightly lower values of K than that of the motion-picture strip seen in Fig. 9. It will be observed that the cavitation seen in Fig. 12a, Plate 5, appears the same as that shown in the strip; whereas that seen in Fig. 12b, Plate 5, seems quite different. This illustrates clearly that there are different types of cavitation, and furthermore, that at least these two types can exist under nearly the same conditions. The differences between these two types will be discussed later, but first an examination will be made of the similarities, which are more significant than is obvious at first glance. They are:—

- (1) the cavities first appear at the same point on the guiding surface, that is, at about the point where the vapour pressure is reached;
- (2) the cavitation zones cover the same part of the body;
- (3) the thickness of the cavitation zones seem to be about the same.

Therefore, in these important features the two types of cavitation are equivalent.

* At this point the question might well be asked why there is necessarily a void. Why should not a liquid eddy form at this place between the body and the main flow? One answer is that under the conditions described, the outer surface of the eddy will be at vapour pressure and the core will be at even lower pressure. Thus vapour will form in the core of the eddy and force the outer layers into the surrounding flow where they will be entrained and swept downstream. It seems logical to expect that this process will continue until the whole volume is vapour-filled. From this point of view any separation zone is a potential cavitation zone and will become one if the pressure is sufficiently reduced.

One of the most obvious points of difference is found in the zone immediately downstream from the main cavity region, that is, the zone in which the travelling cavities, seen in Fig. 9, Plate 4, and Fig. 12a, Plate 5, go through several cycles of rebound and collapse. The corresponding history of the fixed type of cavity, typified by Fig. 12b, Plate 5, seems to be that large sections of it are entrained by the flowing stream of liquid and are swept downstream, where they disappear. Fig. 13, Plate 5, shows entrainment on the upper and lower surfaces of a hydrofoil, and Fig. 14, Plate 6, shows motion-pictures strips of this phase of the cavitation phenomenon as it appears in profile on cylindrical bodies with (a) the 1.5 calibre nose, and (b) the hemispherical nose. It should be remembered that this entrainment takes place at the downstream end of the low-pressure zone, and collapse and disappearance occurs in a region where the pressure is above vapour pressure. In this type of cavitation the cavity elements are extremely irregular in shape and by no stretch of imagination could be considered as spheres. Thus the mechanics of their collapse is very complicated; presumably, much of the energy associated with it is dissipated in the process, as it is difficult to find clear evidence of repeated rebounds and recollapses. It should be emphasized that, even with this apparent difference in appearance, these parts of the cavitation process are basically similar for the two types.

Analysis of Cavity Collapse. In collapse of the spherical travelling cavities it is possible, on the basis of some simple assumptions, to calculate the size of the cavity from the time it has reached its maximum diameter until it has completely collapsed. This was first done by Lord Rayleigh (1917), who considered the collapse of an empty spherical cavity in an incompressible fluid, having a constant pressure at infinity. He equated the kinetic energy of the resulting motion of the fluid to the work done at infinity by the constant pressure acting through a change of volume equal to the change of the cavity volume. Fig. 15 gives a comparison of the observed collapse with

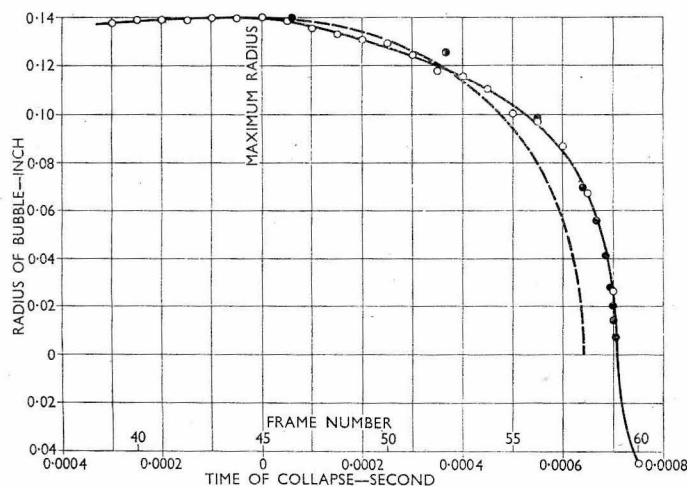


Fig. 15. Comparison of Bubble Size with Rayleigh Prediction

- Bubble measured from photographs.
- — — Rayleigh theoretical curve from equal maximum diameter and pressure difference.
- Rayleigh theoretical points for maximum diameter and time.

that predicted on the basis of these simple assumptions. It will be seen that the agreement is surprisingly good, so good that it leaves little reason to doubt that the basic mechanics are as Lord Rayleigh visualized. He also calculated the pressure that would result if the cavity collapsed concentrically on to a small,

* The reason for assuming the existence of the sphere is to obtain a finite collapse velocity, since, for a perfect incompressible fluid the collapse velocity approaches infinity as the radius of curvature approaches zero. This assumption would not be necessary if the calculations could be made for a real compressible fluid.

infinitely rigid sphere*. He abandoned the assumption of the incompressible fluid at the instant that the cavity wall touched the surface of the sphere, and proceeded to determine the pressure on the surface of the sphere on the basis that the kinetic energy present in the liquid just before the instant of contact was converted to potential energy of compression as the liquid came to rest. This is the same physical picture that underlies all calculations of water-hammer pressure. If the slope of the theoretical or experimental curve in Fig. 15 is used to compute the radial velocity of the water as the bubble radius approaches zero, it will be found that, even for this small bubble, these velocities are measured in hundreds of feet per second. Thus the maximum pressures obtained must be very high, certainly of the same order as the elastic limits of metals used in hydraulic machinery.

Cavitation Noise. The prediction of these high pressures during the collapse phase sheds some light on another aspect of the cavitation phenomenon. Everyone familiar with cavitation is aware that the process is noisy. The collapse zone must be a very effective sound source. The pressures are high and the pressure fronts are steep. Undoubtedly some of the energy involved will be dissipated in the form of pressure pulses. This probably accounts, in part, for the damping observed between the successive rebounds of the cavity whose history is plotted in Fig. 10. It might be mentioned in passing that many investigators have found it discouraging to work in a field that Lord Rayleigh has reaped. The gleanings of what little is left of the harvest usually requires a large amount of labour. Certainly the best of the crop is gone. Thus in the analysis of the collapse of these cavities, it is obvious that the liquid is not incompressible nor infinite in extent and the pressure is not constant at the boundary. Furthermore, the cavity is not empty but is vapour-filled and possibly contains some permanent gas. The amount of higher mathematics and labour required to make even approximate corrections for these additional factors is very discouraging, especially when a second glance at Fig. 15 shows that Lord Rayleigh's predictions are correct to within 10 per cent.

Cavitation Nuclei. It is apparent from a continued comparison of Fig. 12a and b that, although in many essentials these cavities are equivalent, there are major differences, at least in the details of cavity formation and collapse. Thus it is a challenge to try to clarify some of the reasons for this difference. A consideration of this phase of the problem quickly leads to the investigation of the mechanics of cavity formation in a homogeneous liquid. The first reaction of the average individual, whether or not he be technically trained, is that nothing could be easier than to create a cavity in a liquid. Apparently, all that is necessary is to attempt to apply a tension to the liquid, and it will rupture. At least, all the common liquids seem to have no tensile strength. However, even a brief survey of the literature on the subject shows that this common belief is erroneous and that, if a liquid is truly homogeneous, it can support a high tension. Therefore, cavities should not be expected to form when vapour pressure is reached. The next thought that arises is that most liquids, and certainly water, contain a relatively large amount of air in solution, and that this air would "obviously" destroy the ability of the liquid to sustain tension. More careful investigation shows that this is not at all obvious.

About a decade ago, Professor Newton Harvey (Harvey, McElroy, and Whiteley 1947) put samples of air-saturated water in a cylinder and compressed them for a few minutes at about 10,000 lb. per sq. in. He then removed them and tested their tensile strength. He found that after this simple treatment many of the test samples would stand tensions of 300–400 lb. per sq. in. This indicates clearly that dissolved gas in itself does not destroy the tensile strength of a liquid. Harvey assumed that the effective tensile strength of the ordinary liquid was destroyed by the presence of large numbers of small, undissolved gas nuclei, and that each nucleus represented a rupture of the liquid. This assumption implies that any nucleus can be made to grow into a cavity of any desired size if the pressure is reduced to that of vapour. One difficulty of this simple concept of the nucleus is that surface tension forces on very small spherical bubbles are tremendous, and would tend to raise the pressure of the gas

in the bubble to such high values that it would be forced to dissolve completely in the liquid, thus destroying the nucleus. To eliminate this difficulty, Harvey assumed that the tiny gas cavities are located in crevices on small hydrophobic (non-wetting) solid particles, such as dust particles, which are present in great numbers in water and most liquids. One of the objectives of his pressure experiments was to demonstrate the possible existence of this type of nucleus. He reasoned that if the pressure on the liquid were raised to a high enough point, the gas pockets on the solid particles would be forced to dissolve, and then the liquid would be able to withstand a tension. Harvey's experiments have been repeated and are now being extended in the Hydrodynamics Laboratory. His results have been confirmed. One of the simplest methods of measuring change in tensile strength, both before and after the pressure treatment, is the determination of the boiling point of the liquid at atmospheric pressure. In Pasadena this boiling point averages about 211 deg. F. However, after pressurizing, samples have been found that do not boil until they have been heated to over 450 deg. F. A glance at the steam table shows that this implies a tensile strength of over 400 lb. per sq. in. Cavitation in such water would be nearly impossible at any velocity normally encountered in engineering practice.

Effect of Nuclei on Cavitation Type. If the need for an existence of these nuclei is tentatively accepted, the explanation of some of the observed cavitation phenomena is simplified. However, it is necessary first to consider in more detail some of the other nuclear characteristics. If these nuclei exist, there is reason to suppose that they may be found in a wide variety of sizes, the largest ones being at least large enough to be seen in a strong beam of light, while the smallest ones may well be below the range of the most powerful microscope. If cavitation is investigated in a stream of liquid containing a supply of relatively large nuclei, it would be expected that visible cavitation would appear just as soon as the lowest pressure in the system reached that of vapour, because one of these large nuclei could grow into a visible bubble practically instantaneously. However, if the liquid contained only extremely small nuclei, it would be anticipated that a relatively long growth period would be required before they would become large enough to be observed or, indeed, to make an appreciable difference in the flow. Thus if the low-pressure region in the test were a very short one, a nucleus might pass through it without ever forming a visible cavity. If the pressure were reduced well below that of vapour, all sizes of nuclei would be expected to have an accelerated rate of growth.

This discussion implies that if a given body were tested for cavitation inception in two different streams of liquid, one containing large and the other very small nuclei, two different results would be obtained. The body would be expected to cavitate at a higher value of K in the liquid containing the large nuclei, that is, its cavitation resistance would be lower than in the other stream. This is unfortunate, because it would be much more convenient if the cavitation resistance as measured by K_i would prove to be a property of the body alone and not also of the liquid. It will be recalled that in the previous discussion of the behaviour of a fluid element or filament it was tacitly assumed that liquid cannot sustain a tension, and that it breaks away from the body when vapour pressure is reached. The discussion of the growth of cavities from nuclei implies that the cavities move with the stream. If a nucleus, even a small one, should be at rest, or nearly at rest, with respect to the surface of the body, instead of moving at the velocity of the stream, then the time available for growth would be greatly increased, but the resulting cavity would be fixed with respect to the body instead of travelling downstream with the liquid. This alternative seems to offer a mechanism by which sufficient cavity volume can be formed to relieve tension in a liquid in which the nuclei may be too small or too few to permit the formation and growth of an adequate volume of travelling cavities.

It is now possible to advance a tentative explanation of the two different types of cavitation that were observed to occur under apparently the same flow conditions. Fig. 12a, Plate 5, was made when the tunnel was operating under conditions favouring the existence of large nuclei. The water was maintained saturated

with air at atmospheric pressure, and a portion of the flow was circulated constantly over either a free-fall or a spray-type cooling tower, in which there was ample opportunity for large nuclei to be formed. The conditions of the liquid under which Fig. 12b was obtained are quite different. Here the tunnel was operating with a completely closed circuit, cooling was done through a heat interchanger, and a resorber had been added to the system, in which each element of the liquid was held at a pressure well above atmosphere for 80 per cent of the time. These circuit changes should act to decrease continuously the number of large nuclei originally present in the water; thus making cavitation increasingly difficult to produce, and increasing the probability of the development of the fixed type of cavitation seen in Fig. 12b, Plate 5, instead of the travelling cavity type found in Fig. 12a.

Cavitation Scale Effect. One of the constant difficulties experienced by both the laboratory research man and the designer is the effect of size or scale in the application of experimental results. The problem is as follows: here are some measurements made on small-size equipment under laboratory conditions. How must they be modified if they are to be used to predict field performance where the size of the equipment will be many times as great? When cavitation is involved it is beginning to appear that this question is intimately related to the properties of the liquid, particularly to the concentration and size distribution of the nuclei. It is probably too early to make the positive assertion that nuclei do exist, that they can be found in a wide range of sizes, and that they are responsible for the otherwise anomalous cavitation performance frequently observed in the laboratory. However, it can be said that cavitation experiments, carried out under carefully controlled conditions, do indicate that at least water exhibits properties that can be explained by the presence of nuclei, and that if the existence of nuclei were ruled out, some other explanation would have to be found for these properties. Therefore, for the present it seems justifiable to accept tentatively their existence, and to see how much help can be obtained from this concept toward increasing the understanding of the behaviour of cavitation.

If the effect of size be considered on this basis, some simple inferences can be drawn. Consider first a liquid containing an ample supply of large nuclei. (It will be remembered that the nuclei are considered large if visible cavities form as soon as vapour pressure is reached.) To all intents and purposes this liquid behaves as an idealized liquid of zero tensile strength. There is no reason to expect any appreciable scale effect with such a liquid, that is, laboratory and field equipment should have the same cavitation performance. Furthermore, in the laboratory the same results should be obtained at different velocities or with different sizes of apparatus. Under such conditions the cavitation characteristics will be a function purely of the geometry of the body; the properties of the liquid have no effect*.

Consider next a liquid containing an ample supply of small nuclei, so small that the time required to form a macroscopic cavity would represent an appreciable distance of travel along the surface of the body. If a series of bodies of the same geometric shape but of different size were tested for cavitation characteristics in a stream of this liquid at a series of different velocities, a definite pattern of performance would be expected. Assume first that all the bodies were tested at the same speed. Since the time required for a fluid element to pass through similar pressure zones will vary directly with the size of the body, it would be expected that for equal values of K less relative amounts of cavitation would be observed on the smaller bodies and, furthermore, that the smaller bodies would have lower values of K_i , that is, they would have higher resistance to cavitation. In large-scale field equipment operating with liquid containing the same size and concentration of nuclei, it would be expected that this trend would continue: the larger the equipment the higher the K_i and the poorer the effective cavitation resistance.

It is a little more difficult to predict what might be expected to happen if one given body were tested in the laboratory at a series of different velocities. For the same value of K with the

* This statement assumes sufficiently high Reynolds numbers to ensure similarity of velocity distributions.

higher velocities, the time of traverse of the low-pressure zone will be shorter, since it is inversely proportional to the velocity. On the other hand, for the same value of K , the absolute pressure differences will increase with the square of the velocity. These effects are in opposite directions, since the decreased traverse time tends to reduce the amount of cavitation; whereas, the greater pressure difference tends to increase it. There are some physical and analytical reasons to believe that the effect of the pressure is more significant than that of the time. If this is true, then K_i should rise and the relative amount of cavitation for a given K value should increase as the velocity is increased. Figs. 16

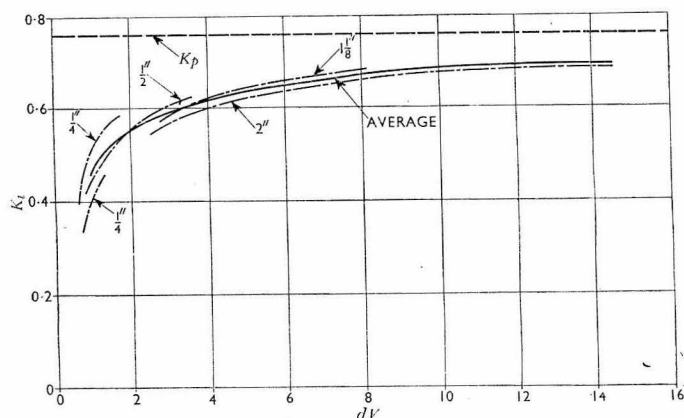


Fig. 16. Effect of Model Size and Flow Velocity on K_i
Hemispherical nose.

and 17 show the measured value of K_i for two series of different sized models, each tested at several different velocities. The experiments on which Fig. 16 is based were made by Kermeen of the Hydrodynamics Laboratory, California Institute of Technology (Kermeen, in Parkin 1951), and those used in Fig. 17 were made by the author. In each series the models are geometrically similar. In Fig. 16 the body is a cylinder with a hemispherical nose. In Fig. 17 it is a cylinder with a 1.5 calibre ogive nose. The test runs of Fig. 16 were taken over a considerable period of time interspersed with other experimental programmes which use the same facility. Some of the runs of Fig. 17 were taken before and some after the entire charge of

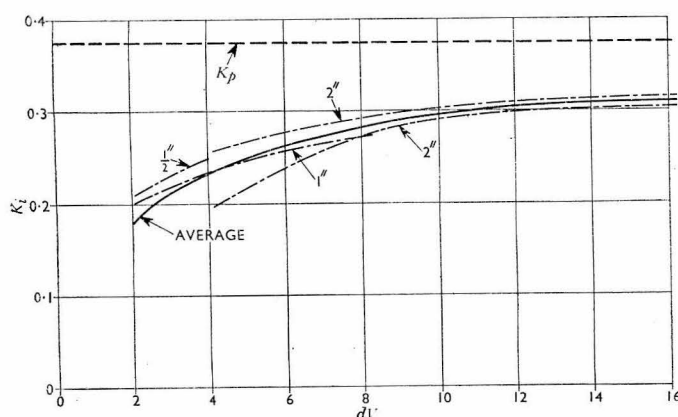


Fig. 17. Effect of Model Size and Flow Velocity on K_i
1.5 calibre ogive nose.

water in the system was changed. It is probable, therefore, that within each series the average size and concentration of the nuclei varied appreciably and major changes might have taken place in these two quantities between the two series.

At first sight it appears that in each series there is evidence of some systematic difference between the curves for the different sized models. However, in each series there are also runs on the

same sized model that differ in value as much as the total spread between the runs for the different sized models. Furthermore, the direction of this trend is not consistent between the two series. Thus the question may be raised whether the differences shown between the characteristics of the various models are due to the variations in size or to differences in the properties of the water used in the individual runs. In both diagrams the full-line curve is the average for all of the runs. Since both of these curves show the same type of variation of K_i with dV , and since it is in the direction to be expected from the reasoning just advanced concerning the properties of nuclei, it seems probable that this represents the basic relation between K_i , the guide surface size, and the flow velocity.

As this evidence indicates a pronounced scale effect, it would be valuable to have some measure both of the magnitude of this effect and its variation with changes in size and velocity. Both Figs. 16 and 17 include a horizontal dotted line K_p showing the value of K_i as determined from the pressure distribution on the surface. This can be considered as a limiting K_i as the body size approaches infinity. Reflection will show that the difference between this value and the observed value of K_i is proportional to the effective liquid tension acting to cause the cavity to form and grow. When the concepts and method used by Lord Rayleigh to calculate the time of collapse of a cavity are applied to estimate the time of growth of a nucleus to a small finite cavity, it is found that this time is proportional to the cavity size divided by the square root of the pressure difference causing the growth. Except for small radius ratios of cavity to nucleus the relation may be expressed as follows:—

$$\frac{t\sqrt{(\Delta p)}}{R_0} = \text{constant} \quad \dots \quad (1)$$

where t is the time of growth of nucleus to radius R_0 and Δp is the effective liquid tension, that is, the pressure difference causing growth. In accordance with the previous remarks, Δp may be expressed as

$$\Delta p = (K_p - K_e)\rho \frac{V^2}{2} = \Delta K \cdot \rho \frac{V^2}{2} \quad \dots \quad (2)$$

where K_p is the value of K_i as estimated from the pressure distribution diagram and K_e is the value of K_i determined from a given test. The time available for growth may be considered to be the length of the negative pressure zone on the body at the relative pressure level K_e , divided by the flow velocity V . An examination of the series of pressure distribution diagrams shown in Fig. 18 shows that this length is roughly proportional to $d\sqrt{(\Delta K)}$, where d is the body diameter. If these expressions for time and pressure difference are substituted into equation (1) it becomes

$$\frac{d\sqrt{(\Delta K)}}{V} \cdot \frac{\sqrt{(\Delta K V^2)}}{R_0} = \frac{d \cdot \Delta K}{R_0} = \text{constant} \quad \dots \quad (3)$$

If the cavitation photographs of the tests (Fig. 17) are examined it is apparent that the average cavity size at incipient cavitation varies both with the diameter of the model and the flow velocity. Apparently the larger the model and the lower the flow velocity the larger is the average cavity size. However, these variations do not seem to be linear with d and V but are apparently less rapid. If the arbitrary assumption is made that R_0 varies as $\sqrt{(d/V)}$ then equation (3) becomes

$$\frac{d \cdot \Delta K}{\sqrt{(d/V)}} = \Delta K \sqrt{(dV)} = \text{constant} \quad \dots \quad (4)$$

Values of $\Delta K \sqrt{(dV)}$ are calculated from the data of Figs. 16 and 17. The results, plotted against the product dV , are shown in Fig. 18*. It is seen that both series are constant within 10 per cent. This suggests the tentative use of equation (4) for predicting the effect of changes in scale on the inception of cavitation.

* The product dV was selected for this calculation and diagram instead of the Reynolds number, Re , because the assumed characteristics of the nuclei do not involve the viscosity and the density of the liquid. The use of Reynolds number would have the advantage of making the equations dimensionless. The laboratory experiments throw ~~new~~ light on this choice since the temperature of the water was practically constant for all of the investigations.

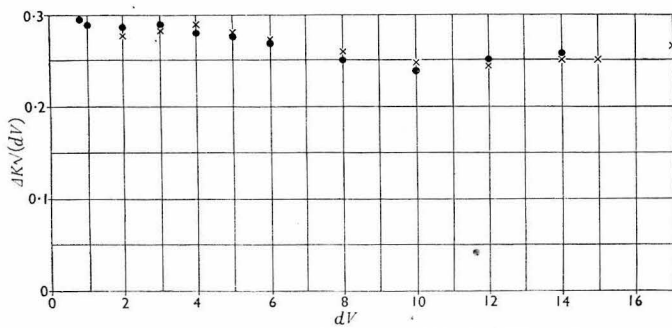


Fig. 18. Experimental Verification of Scale Effect Constant

- × 1.5 calibre ogive nose.
- Hemispherical nose.

For this use, d would represent a characteristic dimension of the body or flow passage, and V the associated velocity.

Effect of Shape on Cavitation Characteristics. Fig. 19, Plate 7, shows the fully developed cavities produced on cylindrical bodies having different nose shapes. It will be observed that these noses are arranged in the order of increasing fineness, from the square-end cylinder to the 2.5 calibre spherogive. Fig. 20 shows the pressure distributions on a family of ogive noses which includes several of the models shown in Fig. 19. These pressure distribution measurements were made at high enough pressure to ensure no cavitation. A careful study of this diagram shows that the area over which the pressure is positive is greater for the blunt-nosed shapes than for the finer nosed shapes, while at the same time the magnitude of the negative pressure is greater. The kinematic requirements are the same in all. The liquid must be moved laterally relative to the solid body just far enough to permit the body to pass through the liquid or the liquid to pass around the body, depending upon which is considered moving and which fixed.

One way of interpreting the effect of the body shape on these

pressure diagrams is to say that more than enough force (positive pressure) is applied by the blunter bodies to the liquid and that consequently a high force in the opposite direction (negative pressure) must be exerted to prevent the liquid from going too far. From this point of view the ideal nose shape would apply just sufficient force to the liquid to cause it to move out of the way of the body without requiring any negative force to keep it from going too far, that is, the pressure distribution diagram would fall only to the zero line but would not go below it at any point on the body. It is interesting to note in passing that the pressure distribution on the new laminar-flow airfoils approaches this ideal. If Fig. 19 is re-examined, it will be observed that the maximum diameter of the cavity is largest for the square-ended cylinder and decreases as the fineness of the end increases. This is very consistent with the concept just discussed since the negative pressure zone is greatly reduced by the cavitation. Indeed, in the limiting case of operation with a cavitation parameter of zero, the negative pressure zone is eliminated.

In the examples shown thus far cavitation has occurred toward the front end of a guiding surface. The pattern for these cases has been that there is an initial pressure rise which causes the flow to move away from the surface. This is followed by the cavitation-producing pressure drop as the guiding surface curves away from the newly established direction of flow. Another very common flow condition in which cavitation is often observed is that in which the guiding surface curves away from a parallel flow. In this case there is no pressure rise. Since the pressure in the parallel flow is fixed, the pressure on the curved surface must decrease until the pressure gradient required to cause the liquid to follow the surface is obtained or until cavitation ensues. Fig. 21, Plate 8, gives examples of cavitation produced under these flow conditions. Although the physical configuration of the guiding surface is quite different in the two flow conditions, the reason that cavitation takes place is still the same, that is, there is not enough available force to cause the liquid to follow the surface as the latter curves away from the prevailing direction of flow.

In this discussion it is assumed that there is no general pressure rise in the direction of flow. In the case of a diverging passage, such as the recovery section of a Venturi meter, there

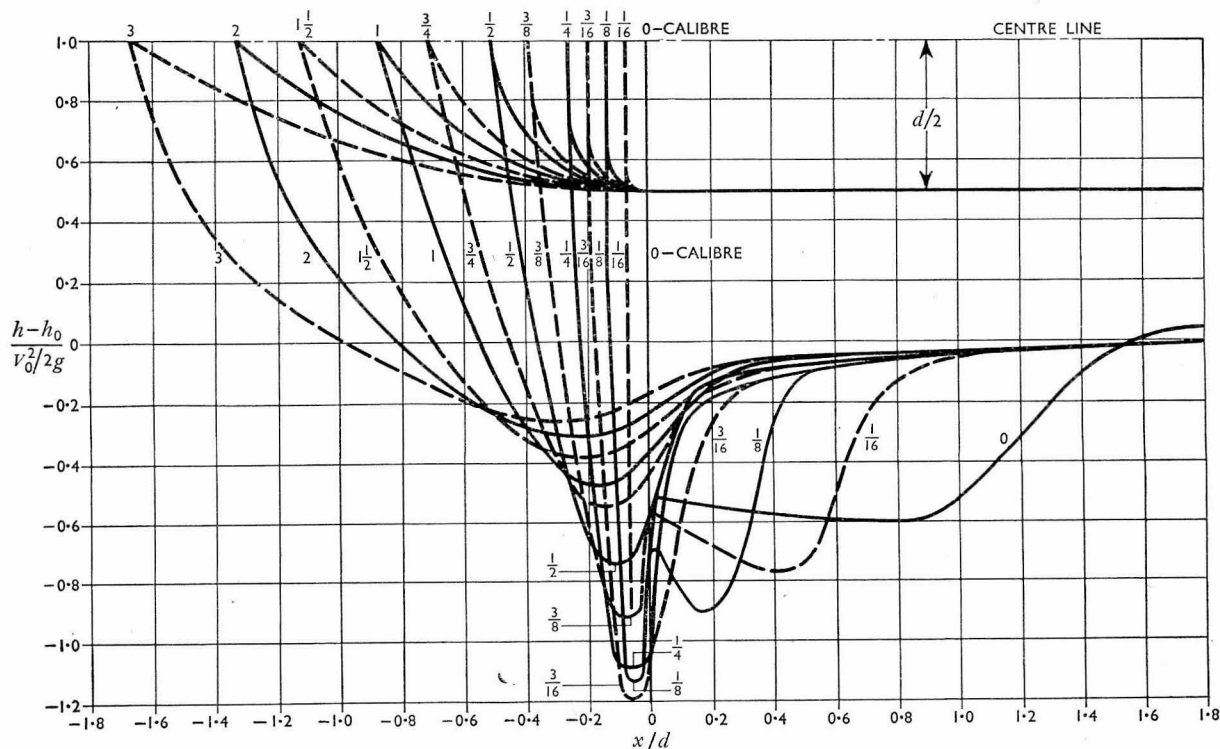


Fig. 20. Pressure Distribution on Family of Ogive Noses

Rouse and McNown 1948.

is such a general pressure rise. This decreases but does not necessarily eliminate the possibility of cavitation, since the general pressure rise may not be great enough to keep the pressure on the diverging surfaces from falling below vapour pressure.

The illustrations presented thus far show bodies oriented parallel with the flow. However, most guiding surfaces do not operate in this manner, but are oriented with a finite angle of attack at the leading edge. This has a pronounced effect on the cavitation characteristics of the flow system. Fig. 22, Plate 8, shows the effect of variations in angle of attack on cavitation for a hydrofoil operating under severe cavitation conditions. These photographs were selected for as nearly the same flow velocity and cavitation parameter as could be obtained, the angle of attack varying from positive to negative. It will be observed that for positive angles of attack, cavitation occurs on the upper surface of the hydrofoil, and for negative angles of attack, on the lower. Fig. 23 shows the effect of variations in angle of attack on the inception of cavitation on this airfoil (N.A.C.A.-4412). As would be expected, the cavitation resistances of the two surfaces are not the same since this is not a symmetrical section. This asymmetry also explains why the optimum angle of attack for cavitation resistance is not zero but -1.5 deg. Fig. 24 shows

the lift and drag characteristics of this airfoil. It will be noted that -1.5 deg. is by no means the zero lift angle for this airfoil, although it is nearly the minimum drag angle.

DESIGN IMPLICATIONS

This discussion has obviously been growing more and more specific; in fact, in the last few sections the implications regarding design of hydraulic equipment are quite clear. In the remaining sections an attempt will be made to apply more of these concepts of the mechanics of cavitation to the general principles of hydraulic design. In some of this discussion the author feels that he will be venturing out on very thin ice. It is hoped that if any major cracks appear, he will be able to reach solid ground again before he gets a ducking.

Prevention of Cavitation in Hydraulic Equipment. The sure way to prevent cavitation in hydraulic equipment operating under critical flow conditions is to avoid any changes of velocity either in magnitude or direction, and to eliminate all fluid friction losses. This exaggerated statement is made to emphasize the fact that it is impossible to design a useful hydraulic machine without some danger of cavitation if the operating conditions are made sufficiently severe. Most hydraulic machines depend for their action on changing the velocity of the liquid. If that cannot be done then the machine cannot operate. Thus the prevention of cavitation must be concerned primarily with finding out just how much the velocity of the liquid can be changed without reducing the local pressure to or below the vapour pressure. Now a change in velocity, as accomplished by a guiding surface which is inclined toward or is concave to the direction of flow, has been seen to produce an increase rather than a decrease in pressure, and hence is not the cause of cavitation at that point. However, if its use demands that it be followed by a portion of the guiding surface which is turned away from or is convex to the direction of flow, then it may be the real cause of cavitation even though the cavitation zone is on the second portion of the surface.

One thing that should be borne in mind is that centrifugal pumps and turbines depend for their operation upon a change of momentum of the fluid that flows through them. However, the local pressure on critical surfaces is determined not only by the total momentum change, but also by the local radius of curvature. It is, of course, possible to design an infinite number of passages with different radii of curvature, all of which will produce the same total momentum change. Another fact which should be remembered is that the centre-line of a guiding vane may be designed to have ideal curvatures for the prevention of cavitation, but still the vane may cavitate badly if its cross-section is not properly designed. Too sharp a radius of curvature from the leading edge to the point of maximum thickness can prevent the realization of the potentially good performance of a well-designed centre-line. One practical difficulty in the design of cavitation-resistant pumps, turbines, propellers, etc., is that none of these machines operates all of the time under its best performance conditions. Each one must work satisfactorily under a range of lower and higher loads. Thus the angle of approach of the liquid to the guiding surface must vary. To meet these conditions it is necessary to choose a guide-vane profile that will have the smallest variation of the minimum pressures over this range of angle of approach. If a profile is chosen that is sensitive to variations in angle of attack, then there is danger of serious cavitation in a part of the operating range, even though the cavitation performance may be very good for operation at the design load.

In the consideration of the cavitation performance of various types of hydraulic machine, there are inherent differences in the adaptabilities of these machines for satisfactory operation under off-design conditions. The usual type of centrifugal pump has no adjustable guide surfaces. Thus it is the least adaptable to variations in operating conditions. The Francis turbine has a set of adjustable guide vanes just upstream from the runner. They increase considerably the adaptability of the machine to variations in operating conditions. The Kaplan turbine not only has similar adjustable guide vanes in the casing, but also has adjustable runner blades. Therefore, it has the greatest adapt-

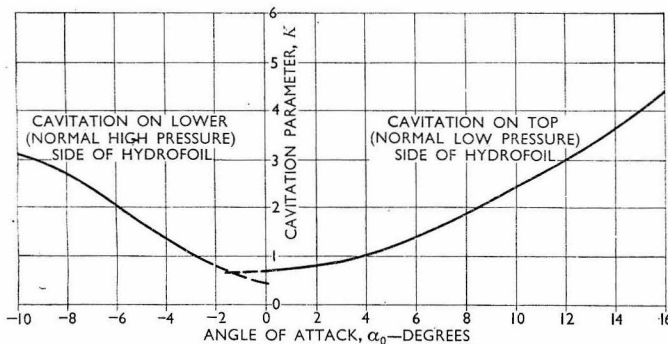


Fig. 23. Cavitation Characteristics of Hydrofoil N.A.C.A.-4412

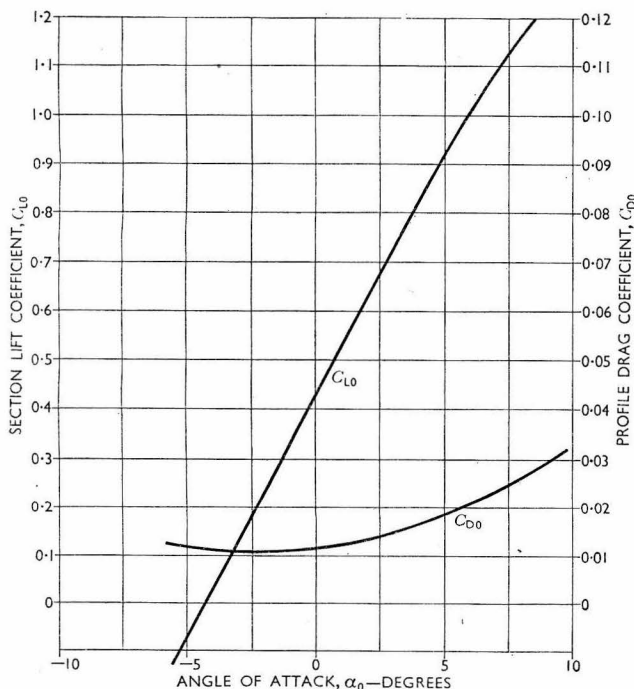


Fig. 24. Lift and Drag Characteristics of Hydrofoil N.A.C.A.-4412

ability to changes in the conditions of operation. For this reason the skill required to design a machine well adapted to cavitation-free operation over a wide range of conditions is greatest for the centrifugal pump. The operator can compensate, at least in part, for mistakes in the original design if he has one set of adjustable guide vanes in his machine, and can accomplish even more in this direction if he has two sets.

The hydraulic designer can profit greatly from a study of the pressure distribution on the many airfoil profiles for which measurements are available. For fixed guide vanes the aerodynamic data are directly applicable. For the calculation of K_i care must be taken to use the correct Reynolds number and to make allowance for interference effects. Moving guide vanes are another matter. They can be divided into two broad classes: those operating at constant stream pressure, and those in a variable pressure field. The free stream propeller, that is, the ship's propeller, is typical of the first class. In this and similar applications aerodynamic data can be used quantitatively. The direct application of aerodynamic pressure distribution data to moving guide vanes operating in a variable pressure field is another matter. Airfoil data are obtained experimentally in constant pressure flows. The technique for extrapolating to variable pressure flows is not clear; hence for the time being, such data can be used most profitably in a qualitative manner. Moving guide vanes of this type are typical of the runners of hydraulic turbines and centrifugal pumps. In such machines there are many other complicating factors such as mutual interference between the vanes, interference between the vanes and the shrouds, and last, but by no means least, variations due to the flow being definitely three-dimensional. Although these complications make it impossible to calculate the details of the pressure distribution on vanes of hydraulic machines, they do not prevent the application of the general principles which have become clear from the study of the cavitation process. A few such conclusions will now be enumerated:—

(1) In most hydraulic designs it is possible at an early stage to estimate both the average pressure and the average velocity at all cross-sections of flow. The cavitation parameter calculated from these estimates will serve to indicate the danger zones in the design. It will be found that these zones are not always restricted to the minimum pressure regions, but may sometimes occur where the pressure is relatively high, provided that the velocity is likewise high.

(2) The leading edges of all guiding surfaces should be examined for all required conditions of flow, particularly those which may result in an angle of attack that deviates markedly from the optimum. In this connexion a second glance at Fig. 22 is illuminating. The N.A.C.A.-4412 is a relatively thick vane, so its cavitation parameter for the optimum angle of attack is 0.7, a moderately high figure. However, for a positive angle of attack of 10 deg. this increases to 2.5, and for -10 deg. it is about 3.1. The latter is about four-and-one-half times the parameter for the optimum conditions. Consider the behaviour of this vane in a relatively high-pressure flow, as for example, if it were used as the casing tongue in a centrifugal pump. Assume the absolute pressure of the fluid, measured in feet, is 100. At the optimum angle of attack this vane would not cavitate until the velocity exceeded 96 ft. per sec. If the angle of attack were changed to -10 deg., cavitation would begin when the velocity reached 45 ft. per sec.

(3) For moving guide vanes operating under critical cavitation conditions, the load on the low-pressure side should be kept small. As the flow cavitation parameter increases, the load on this side of the vane may be increased.

(4) Guide vane curvature should be watched carefully in all critical regions. Discontinuities in slope are very serious. Although the effects are less marked, discontinuities in the radius of curvature produce pressure disturbances even though the two sections of the curve are tangent. It is probable that discontinuities in the rate of change of curvature, that is, the second derivative, also produce undesirable disturbances, but they should not be as serious as the other two. Although discontinuities in slope may be detected easily, the eye is not a good judge of discontinuities in radius of curvature or rate of change of curvature. For example, consider two noses for a cylindrical body, one an ogive and the other an ellipsoid.

Assume that each is one calibre long. The ogive (1.3 calibre) cavitates at about $K_i = 0.42$. The ellipsoid (axis ratio of 2) cavitates at about $K_i = 0.33$. To the eye the ellipsoidal nose appears blunter and certainly has the larger volume. However, its cavitation resistance is considerably better. At the same time it is a physically stronger section and more easily manufactured.

(5) The surface roughness, if its scale approaches or exceeds that of the laminar boundary layer, will probably cause local cavitation on an otherwise cavitation-free surface.

Prediction of Cavitation Performance from Laboratory Tests. The above items are concerned primarily with questions of design. An additional comment may be in order with regard to the testing of hydraulic machinery to determine its cavitation characteristics. During the discussion of the mechanics of cavitation, the effects of variations of both size and velocity were considered. It was seen that there was some experimental evidence to indicate that for a given geometrical configuration, the relation expressed in equation (4) holds for variations in both pressure and size, and that therefore it might form the basis of an empirical method that could be used tentatively for predicting the effect of changes in scale. One of the serious questions which arise in connexion with the laboratory testing of a small-scale model of a large hydraulic machine such as a pump or turbine, is concerned with the prediction of the cavitation performance of the large machine from the laboratory test results on the small one. At first sight it might be concluded that it would be impossible to use equation (4) to make this extrapolation, since it would seem necessary to know the value of K_p . In many cases it might require a prohibitive amount of time and effort to determine the pressure distribution experimentally. In the model tests it is quite easy to determine the operating conditions at which cavitation commences, but the measurements do not necessarily give a clue as to the point within the machine at which the cavitation is occurring. If investigation showed the cavitation to be located on a fixed guide surface, the extra work required for the installation of a series of piezometer openings might be justified. On the other hand, if, as is common, the cavitation first occurred on one of the moving guide surfaces, the experimental difficulties would be magnified greatly.

A further examination of the proposed method of extrapolation shows that there is a simple alternative. If similar tests can be made at two different operating conditions, but with the identical liquid, the results may be expressed in the two parallel equations:—

$$C = (K_p - K_{e1}) \cdot \sqrt{(d_1 V_1)}$$

$$C = (K_p - K_{e2}) \cdot \sqrt{(d_2 V_2)}$$

where d and V are characteristic dimensions and velocities for the two tests. The test conditions should be chosen to give the maximum difference between $d_1 V_1$ and $d_2 V_2$ that is consistent with good test accuracy. In these two expressions the two unknowns are C and K_p . If C is eliminated, the following expression is obtained for K_p :—

$$K_p = \frac{K_{e1} \cdot \sqrt{(d_1 V_1)} - K_{e2} \cdot \sqrt{(d_2 V_2)}}{\sqrt{(d_1 V_1)} - \sqrt{(d_2 V_2)}}$$

Obviously, the required variation in the $\sqrt{(dV)}$ may be obtained by varying either the size of the model or the velocity of the flow. With K_p determined in this manner the way is clear for the prediction of the cavitation performance of the prototype. Before this final step is taken, however, it would be well to consider whether or not the pertinent characteristics of the prototype liquid can be expected to be the same as of the liquid used in the laboratory. If the constant, C , determined from the two laboratory tests, is used directly to predict the K_e value for the prototype machine, it implies that the two liquids are identical. This assumption is probably acceptable if the values of K_{e1} and K_{e2} differ only slightly from that of K_p , or if there are physical measurements available to confirm the similarity of the two liquids. However, as previously pointed out, most natural water supplies probably contain a sufficient number of large nuclei for cavitation to be expected to appear when the pressure reaches that of vapour pressure. If the values K_{e1} and K_{e2} differ appreciably from that of K_p , it is implied that the laboratory water supply does not contain the normal concentration of large nuclei. Thus the

more conservative method of extrapolation to the field operating condition would be to assume that the machine will cavitate at K_p .

Effect of Cavitation on Performance. Little can be added to the statements in the introductory paragraph concerning the effects of cavitation on the performance of hydraulic machines. The typical effects which accompany the onset of cavitation are loss of efficiency and decrease of power output or head produced. These are the effects that would be expected from local cavitation, as it acts to increase the resistance in the passages and to decrease the change in angular momentum produced by the rotating element. As cavitation develops more fully the performance of the unit completely breaks down. There seem to be two possible explanations for this breakdown. If the machine is poorly designed as regards cavitation, it is probable that, as cavitation develops, the volume occupied by the cavities originating at the guiding surface decreases the useful area of the passages to such an extent that it effectively limits the flow. In this case the average pressure in the main body of the stream at this cross-section may be considerably above the vapour pressure. Under such conditions the breakdown performance of the machine could be improved by the employment of better vane cross-sections and angles of attack.

The second explanation for the performance breakdown would apply to a machine having a very good design. In this case the average pressure at a given cross-section would approach closely that of the minimum pressure on the guiding surface. Under such conditions, as cavitation develops the pressure in the entire stream may drop to vapour pressure. Vapour bubbles would then form, not only on the guiding surface, but also throughout the cross-section, and their volume would be limited only by the pressure differential available to cause vaporization. This sets an absolute limit for the performance of the machine. Even for a perfect design there would be, for each system pressure, a certain rate of flow at which this performance limit would be reached.

CAVITATION DAMAGE

This lecture has been confined to the consideration of the mechanics of cavitation; questions of the relative resistance of materials to cavitation damage have been specifically excluded. In the present state of knowledge concerning the hydrodynamics of cavitation damage, there is little that can be said, even tentatively, with regard to design trends that might be expected to decrease the amount of damage if a machine must be operated under cavitating conditions. One or two general remarks may be made, primarily for the purpose of stimulating thought and discussion.

With our present understanding of the cavitation process, the most plausible cause of cavitation damage seems to be the high local pressures which occur at the completion of collapse of a cavity due to the "water hammer" effect, that is, the storing of the kinetic energy as elastic compression of the liquid. Lord Rayleigh's calculations of this collapse pressure show that it varies as the three-halves power of the cavity diameter and the square root of the system pressure. For a given velocity in a specific liquid the average cavity dimension probably varies with the lateral dimension of the cavitation zone. It has been seen that this dimension is relatively large for blunt bodies with high K_i values and decreases as the cavitation resistance increases. Also, the fact that cavitation occurs at a relatively high value of K means that the collapse zone will be at a higher pressure than it would be if the surface had a better shape and, consequently, a lower K_i value. All of this points to the conclusion that a well-designed machine which has a low K_i value will probably be subject to less cavitation damage than will a similar machine having a high K_i value, even though both machines are operated at approximately the same degree of cavitation. This is fortunate, if true, because it implies that the design which would be the most effective in preventing cavitation should also, if operated at the same load but under cavitating conditions, be expected to show the minimum degradation of performance and the least amount of cavitation damage.

There has been considerable speculation concerning the scale

effect, that is, the effect of absolute size, on cavitation damage. This is an even more complicated subject than the effect of scale on the inception of cavitation. It will be remembered that earlier in the paper, when this effect was discussed, it was pointed out that there were two independent elements involved: the geometry of the flow, and the properties of the liquid. Since as yet it is not definitely known what are the pertinent properties of the liquid, all statements regarding the effect of scale on the inception of cavitation must be considered speculative. The situation is even worse in the case of cavitation damage. Another element has to be considered, that is, the properties of the material that is being damaged.

It has been the author's expressed opinion for some time that a rational study of cavitation damage cannot be made until a good working knowledge of the mechanics of cavitation is available, since it will be difficult to understand the reaction of a solid to a *known* external force system. It would appear that such time is approaching. The present state of knowledge of the mechanics of cavitation, although far from complete, is beginning to form a consistent picture, and may now be adequate to justify preliminary investigations of the inception of cavitation damage.

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APPENDIX

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